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METEOROLOGICAL RESEARCH IN AIRCRAFT.

by

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(Meteorological Office)

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AIR MINISTRY

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FOREWORD

Meteorology, the science of the atmosphere, has a long history with important applications to many sides of human activity, but nowhere has the application been more direct or more vital than in aviation. In the design of aircraft, for the long-term planning of civil air-routes or military operations, and for the safe, efficient and effective execution of day-to-day operations in peace and war, the advice of the meteorologist has been and continues to be essential and often critical: the debt which aviation owes to meteorology is immeasurable. But the account has never been one-sided and the contributions to meteorological knowledge provided by the observer in the aircraft began with the earliest days of flying and continue to grow in scope and importance as new aircraft are developed, and new instrumentation in the hands of expert meteorologists is carried wherever the aircraft will reach.

The account here presented describes the work of the Meteorological Research Flight, an integral part of the research organization of the Meteorological Office, with aircraft instrumented and manned by scientific staff directing their whole time to the solution of problems for which the aircraft is an eminently suitable and, in many respects, an irreplaceable tool. The author has been for some years the Senior Meteorological Officer of the Flight and has been personally responsible for the design and installation of much of the technical equipment as well as for supervising the execution of the research itself. There could be no-one better fitted to prepare such a report and it is believed that it will be of wide interest and value.

Few, if any, other meteorological organizations in the world have hitherto been so fortunately placed with aircraft continuously and exclusively provided for meteorological research. The present account indicates the wealth of information which these facilities bring within the reach of the meteorologist and should be an encouragement to other services which may be contemplating similar establishments.

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1. Introduction

Although the use of aircraft for routine observations of wind, temperature, and humidity in the upper air has almost everywhere given way to that of radio and radar-sonde balloons, the aircraft has several unique advantages as a tool for special observations needed for research purposes. These derive mainly from its ability to travel at will to selected positions and to carry a number of observers and complicated apparatus. With modern aircraft and specialised instrumentation the field of meteorological measurements at altitudes up to 50,000 feet is very wide, and includes all types of nuclei and dust particles, the chemical constituents of the atmosphere, the composition and structure of clouds, rainfall mechanisms, electrical phenomena, radiation measurements, turbulence and diffusion recordings and detailed studies of large weather systems made in conjunction with large-scale synoptic observations. The difficulties in operating an organisation to do this work are, however, considerable and for economic reasons the organisation must be able to utilise fully the aircraft allocated to it. Aircraft are expensive. Research flights of many types can not be made in areas where there are civil airways or military restrictions. The instrumentation must be such that accurate measurements are obtained at high speeds and in bumpy conditions and the mounting and location of instruments on the aircraft must be such that the readings are representative of conditions in air undisturbed by the presence of the aircraft. The data obtained on a single flight may result in weeks of analysis and study before they can be fully assimilated. A considerable backing of scientific and technical manpower is therefore needed both to devise the instrumentation and digest the results obtained.

During the second World War 1939-45 the Meteorological Office operated aircraft as part of the High Altitude Flight at Boscombe Down to make specialised measurements and at the end of the war formed the Meteorological Research Flight at R.A.E. Farnborough. At present this is believed to be the only institution in the world equipped on a regular basis to deal with all types of meteorological measurements. It is the purpose of this article to describe some of the results obtained up to date and outline the work now being carried out and its prospects for the future. Most of the space will be devoted to methods of measurement and it will only be possible to indicate very briefly in a short article of this type how the results of the measurements are being utilised.

2. Measurements at high altitudes

For high-level and high-speed work, a Canberra aircraft is used with a ceiling of about 50,000 ft. and the chief measurements made at present with this machine are summarised in the next paragraph.

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2.1. Temperature

Owing to kinetic and friction effects the indicated temperature of a thermometer in a moving airstream of true air-speed V is greater than the air temperature by an amount KV^2, where, under given conditions, K is a constant. The term KV^2 may be about $40^{\circ}F$ when V is 500 kt. and hence small variations of K due to the thermometer's design and position on the aircraft structure will produce important errors in the measured temperature. Studies of this latter effect and improvements in aircraft thermometers, made in collaboration with the Meteorological Office at Harrow, have resulted in various electrical resistance thermometers for use in aircraft, which are shown in Fig.1. A comparatively recent American suggestion (Refs.1 and 2) for eliminating the effect of aircraft-speed has been to mount the thermometer element at the centre of a vortex, where it will undergo cooling which can be adjusted to offset the heating induced by kinetic effects. Models of these vortex thermometers of both the tangential type, and the axial flow type shown in Fig.1, have been tested in flight up to 40,000 ft. and shown to be efficient in clear air. In cloudy air the performance of all conventional thermometers is affected by partial evaporation of the water deposited, or the ice formed, on their surfaces and it has not yet proved possible to obtain reliable temperature readings in cloud. The accuracy required here is about $\pm 1^{\circ}F$, for use in calculations of buoyancy in the development of cumulus clouds for example. It may be that it will prove impossible to design simple thermometers which will give readings of this accuracy in cloud, and that more complicated instruments such as sonic or radiation thermometers will have to be developed for this purpose. This problem is discussed in more detail below.

2.2. Humidity

The difficulty in measuring humidity at high levels, particularly in the stratosphere, arises from the minute quantity of water there. The instrument in use at present (which was designed for this work) is the Dobson-Brewer hygrometer (Ref.3) which consists essentially of a cooled surface whose temperature can be controlled and measured. The temperature at which a frost deposit first appears when air is passed over it is the frost point of the air. In an automatic version of this instrument the surface is viewed by a photo-electric cell whose output controls the surface temperature at the frost point through suitable electronic circuits. For high-altitude work the instrument has to be pressurised so that it can be operated with outside air while it is within the pressure cabin. It is also advantageous at high levels to compress the air to a high pressure before reading its frost point and in a recent adaptation the air is passed through the compressor of the jet aircraft in which the measurement is made before its humidity is measured (Ref.4).

The results of this work (Refs.5 and 6) show that the stratosphere over England is very dry and that the frost point at 50,000 ft. is usually about $-115^{\circ}F$ (Fig.2). The most likely explanation of these low frost points is that air in the lower stratosphere over temperate latitudes must recently have passed through the equatorial tropopause (Ref.7). It has been planned to extend these humidity measurements, together with those of ozone, to other latitudes to obtain more information on the way they vary, and hence on the general changes of circulation at high levels, as well as to utilise them in more obvious ways for forecasting high cloud and condensation trails and as data in radiation studies.

The most commonly occurring condensation trails are formed at high altitudes and arise from the addition of exhaust water vapour to the air behind the aircraft. The study of this process, and of the effects of exhaust heat and the mixing of the exhaust gases with the air at high altitudes, involves a knowledge of the aircraft-engine performance as well as the meteorological factors involved (Ref.8). Fig.4 shows photographs of contrails taken during some of these studies. The conditions for the formation of high cloud are at present not well understood but a great deal of data on its occurrence, temperature, height and extent have been collected (Fig.3 and Ref.9). Studies of radiation are discussed further below.

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2.3. Ozone

Another parameter of importance in the study of circulation and radiative equilibrium in the upper troposphere and lower stratosphere is the amount of ozone in the atmosphere at these levels. The apparatus shown in Fig.5 is an adaptation, by the Meteorological Department of the Clarendon Laboratory, Oxford University and the Meteorological Research Flight, of a system due to Ehmert (Ref.10) of determining chemically the ozone-content of air, and has been used in the stratosphere in jet aircraft. Each of the test tubes is arranged by remote control to have 5 litres of air passed through it at chosen levels up to 50,000 ft. They all contain solutions of sodium thiosulphate in an excess of potassium iodide. The effect of ozone passing through this solution is to liberate free iodine from the potassium iodide. This iodine then reacts with some of the sodium thiosulphate and a subsequent electrometrical titration, made on the ground, is directed towards determining the remaining amount of sodium thiosulphate and hence the amount of ozone originally sampled. The chemical equations for this process are:

$$O_3 + 2\,KI + H_2O = 2\,KOH + O_2 + I_2$$

$$2\,Na_2S_2O_3 + I_2 = 2\,NaI + Na_2S_4O_6$$

The results in the troposphere in England are in agreement with previous work (Ref.11) and show small amounts, considerable variability and little change with height. Measurements of ozone-content in the stratosphere so far have not been consistent enough to reveal any well-marked features and further measurements are to be made in the near future. In England (latitude 50°N) the measurements up to date have not shown any marked increase at the tropopause but rather a tendency for the increase with height to become more evident at about 50,000 ft. Some preliminary measurements made by Dr. A.W. Brewer of the Clarendon Laboratory, Oxford University, using this apparatus in Norway (latitude 70°N) have, however, shown significant increases just above the tropopause between 30,000 and 35,000 ft.

2.4. Winds and turbulence

The measurement of wind from aircraft is usually accomplished by comparing its ground-movement with its air-movement over a given time interval. The accuracy depends entirely on the accuracy of the airspeed indicator and of the ground navigation system. At present the measurements are rather crude compared with those that can be achieved by radar-wind methods using balloons, but they have the advantage that variation in space and time can be measured successfully. Other methods of using an aircraft for special wind measurements, e.g. over short periods and short distances, involve the firing of smoke puffs over a camera obscura on the ground, the discharge of smoke trails or the dropping of "window", the movement of which can be tracked by a ground radar station. The latter, together with the camera obscura, is located at the Meteorological Office's radar station at East Hill near Dunstable. Studies of this type provide valuable information on the variability of wind and on turbulence-parameters at high levels (Ref.12).

The occurrence of clear-air turbulence at high levels is a problem of considerable interest to airline operators and aircraft designers. The main difficulty of investigating this phenomenon is to locate it. An aircraft may be flying at a fairly high altitude, say 30,000 ft., in clear smooth air and suddenly enter a region of rough bumpy air which may persist for a hundred miles or so or may be only a few miles in extent. Similarly it is frequently only a few thousand feet in thickness and may be avoided by a slight change of height. The characteristic frequencies of the bumpiness can be examined by means of accelerometers carried on the aircraft. Attempts have been made with some success (Ref.13) to relate its occurrence to large wind shears in the vertical

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or horizontal or to unstable lapse rates - a frequent location being on the cold side of the jet stream. It is also a possibility that the turbulence is produced up to very high altitudes, under certain conditions, by the degeneration of wave motion set off by mountains. A very large effort has been put into the study of clear air turbulence by several agencies, but it is clear that considerably more research will be necessary before it is thoroughly understood.

In connection with investigations of large-scale meteorological systems, such as the jet stream, the Meteorological Research Flight works in conjunction with the Forecasting Research Division at Dunstable. The system is for the aircraft to fly accurate courses making as many instrumental and visual observations as possible, and for the Forecast Division to attempt to relate these to data obtained from synoptic weather-reporting and radio-sonde stations. It is possible in this way to obtain information on the characteristics of these systems which cannot be obtained in any other manner, e.g. the distribution of humidity, cloud and turbulence round a jet stream has been investigated. (Ref.14). A typical cross-section of a jet stream built up from both aircraft and other measurements is shown in Fig.6. Measurements of this type have helped to explain the circulation and vertical motions associated with the jet stream, the high humidity and cloud being almost always located on its warm side.

The above selection of high level investigations is not exhaustive. It is of course possible to sample aerosols of all types at high levels, catch samples of ice crystals in high clouds, and make radiation measurements, for example. Further details of some of these techniques are given below in the section on measurements at lower altitudes.

3. Lower altitudes

3.1. General facilities

At lower altitudes the scope of the work is considerably greater. A large transport aircraft, a Hastings (Figs.7 and 8) which has an effective ceiling of about 25,000 ft., has been transformed into a flying laboratory for this purpose. Whereas the Canberra can carry only one meteorological observer, who works in a cramped position in a pressurised cabin and operates many of his instruments by remote control, six or more observers can work together as a team in the Hastings, sitting at benches with different apparatus and supplied with a variety of power supplies transformed from the aircraft's electrical system. In its early stages of development an instrument may be adjusted and read directly, and later its dial may be photographed or continuous traces of several instruments can be recorded on a multichannel galvanometer.

The design and production of each instrument for measurement of meteorological parameters in the air raises special difficulties of its own. Usually the aircraft is travelling at about 3 miles a minute, so that for most applications an instrumental lag of more than a few seconds is unacceptable, whilst for some a few milliseconds only is allowable. Moreover aspects of strength, stressing and wind loads have to be carefully considered so that the experimental equipment will not constitute a danger to the aircraft's safety. Factors of this type often impose severe limitations on the exposure that can be given to the various probes although it is always the aim to ensure that the measurements made are representative of the actual conditions in the air without the interference of the aircraft.

A summary of the instrumentation available, and some results, will be given below for the main fields of investigation - cloud physics and cloud modification, atmospheric nuclei, radiation and general investigations. The latter includes studies of large scale phenomena, e.g. fronts, wave motions and stratocumulus formation, in conjunction with the Forecast Research Division at Dunstable, and diffusion studies, in conjunction with the Meteorological Section at C.D.E.E. Porton.

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Some of the work does not involve the use of a large amount of special instrumentation and for this a Varsity aircraft which is less well equipped is used.

3.2. Cloud physics

Cloud physics is a very large subject which involves all aspects of the micro- and macrophysics of clouds and includes the study of precipitation-mechanisms and of the environmental conditions in which the clouds develop. A review of some aspects of this work has been given (Ref.15) but for completeness the short description below of the instrumentation will include these as well as other instruments not previously described.

3.2.1. Particle-sampling

3.2.1.1. Cloud droplets

Cloud droplets have diameters ranging from a few microns to about 100μ in most clouds, the smaller sizes being most common in fair-weather cumulus and stratocumulus, and the larger sizes in cumulus congestus and cumulonimbus clouds. Their sampling is accomplished either by direct capture in oil or by measuring the craters they make on impact with a slide covered with a coating of soot or magnesium oxide. Their number is usually of the order of a few hundreds per cubic centimetre and it follows from this that, generally, the impactor used must be capable of exposing the slide for about $\frac{1}{20}$ - $\frac{1}{50}$th of a second. If the interval can be timed and the collection-efficiency of the sampler is nearly unity this method also provides a measurement of the water-content of the air. The sampler-head must be designed to minimize the effects of splash, and in the case of the oil-sampling method the whole operation, including the photography of the sample, must be accomplished very rapidly to avoid coalescence or partial evaporation of the droplets in the oil. Fig.9 shows different types of cloud droplet and raindrop samplers, Fig.10 shows the present arrangement in the aircraft for rapid photography of the droplet-samples immediately after they are taken, and Fig.11 shows typical photographs of samples. Some results of this work are shown in Fig.12, which shows some curves for droplet-concentrations in cumulus clouds in England.

3.2.1.2. Raindrops

Until recently the problem of sampling raindrops in the atmosphere had not received much attention. It is however of great practical importance because of the severe damage which heavy rain and hail can inflict on a high-speed aircraft even in a very short space of time. In physical meteorology, moreover, an understanding of the history of raindrops during their growth and descent is necessary in order to relate the distribution of drop-sizes observed on the ground to the process by which the drops are formed. Direct measurements of falling raindrops are also necessary in certain studies of radar echoes from precipitation. The relatively large size of the raindrop, which is a difficulty in making measurements by oil or similar techniques, can be utilized in systems based on impact with the collecting surface. For small raindrops and intensities a sooted slide or gauze can be used successfully. Fig.9 includes the type of impactor used for this purpose, the time of exposure being about 1 second for a reasonable sample. Fig.13 shows typical results and it can be seen that even snow-flakes can be sampled by this method. A recent development due to Mr. F.J. Bigg and his colleagues of the M.E. Dept. R.A.E. makes use of the deformation of thin foil by impact with the drop, a method which improves with larger droplets and high aircraft speeds. Fig.14 shows an impactor for continuous recording made by the Meteorological Research Flight to utilise this method. An aluminium foil is exposed for a short time in front of a gauze backing and continuous recording is obtained by driving the rotating drum at an appropriate speed.

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3.2.1.3. Ice crystals, snow and hail

Samples of ice crystals in cloud were taken successfully in aircraft up to cirrus levels as long ago as 1943 (Ref.16). In this work an evaporating lacquer on which crystal replicas were imprinted was used. An alternative method (Ref.17) utilising Formvar in an evaporating solvent, such as ethylene dichloride or chloroform, which is in common use for ice-crystal sampling in cloud chambers, has also been adapted for aircraft work. The development of modern high-speed aircraft has however introduced difficulties in obtaining ice-crystal samples unbroken, and special arrangements are necessary when working from a pressurized cabin.

Imprints of small snow-flakes can be obtained in sooted gauzes (Fig.13) and crystals can also be caught in oil and photographed with special precautions.

Hail-sampling has not yet been attempted from aircraft. There are many cases of structural damage produced by hail, and a device based on the force of an impact could almost certainly be made if a sufficiently urgent need arose for it.

3.2.2. Water content

In addition to data on the size and number of the particles constituting cloud, information is required both for cloud-physics studies and practical applications, such as aircraft deicing, of the amount of free water contained in clouds - usually expressed in gm./m.^{3}. The upper limit of this may be in the region of 10 gm./m.^{3} and values of about 1 gm./m.^{3} are usual. Difficulties arise in the design of an instrument for this work owing to the great difference in size between the cloud droplets (a few microns diameter) and the larger raindrops (a few millimetres diameter), and to the different phases of the water sampled (ice, supercooled water, water above freezing). In addition to covering a range up to about 10 g./m.^{3} a successful instrument must have a very small time-lag (preferably less than a second to measure the rapid changes in a cumuliform cloud), have a high collection efficiency for all particle-sizes, and be robust enough to work on an aircraft. No instrument has yet been devised which will satisfy all these requirements, although several types are in use giving results within their various limitations (Ref.18). The calibration of water-content meters also presents problems as it is not easy to reproduce the actual working conditions in the laboratory. The principal types are:-

3.2.2.1. Forward facing scoops. For these to be effective isokinetic sampling must be achieved (i.e. with a 100% collection efficiency), icing difficulties have to be overcome and a sufficiently large volume of air drawn in to make the accurate measurement of the water it contains a feasible proposition. Some success has however been achieved in America with a capillary collection device. Similar considerations apply to systems in which the air is drawn in, heated to evaporate the water it contains and then passed through a humidity-measuring device. At aircraft speeds the time required to evaporate a cloud droplet (which is usually about one-tenth of a second) becomes important, and for a satisfactory measurement of free water with this method, cloud temperature and relative humidity must also be known accurately. Probably, it is sufficient to assume 100% for the latter but the former is not usually known to within ±2°F.

Under this heading may also be included systems of catching a sample of particles in a given volume, finding their sizes and integrating their volumes. Practical considerations of collection efficiency and counting, apart from the prohibitive amount of labour involved, make this method impractical for general use.

3.2.2.2. Conductivity type of measurement. A very successful method at temperatures above the freezing-point is to allow the water to wet a surface for a given time and then to measure the electrical resistance between two contacts

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resting on the surface. The Commonwealth Scientific and Industrial Research Organisation, Australia, have produced an instrument in which paper is used as the surface and continuous records obtained. (Ref.19). The method however fails at temperatures below the freezing-point (as do all other methods based on the absorption of water into a surface).

3.2.2.3. Hot wire instruments. If the cloud droplets impinge on a hot wire and evaporate, the resulting change of electrical resistance of the wire will be a measure of the power supplied for evaporation, and several instruments have been built to utilise this effect for measurement purposes. The process is complicated, as the wire temperature depends on the temperature and speed of the air stream as well as on its water-content. Moreover, the ability of the wire to evaporate the droplets sufficiently rapidly varies with the wire temperature. When this is low, evaporation will be very slow. On the other hand, at very high wire temperatures, a barrier of steam appears to form on the wire which has the effect of preventing the oncoming droplets from impinging on it. Furthermore ice crystals also do not appear to remain on the wire sufficiently long to be evaporated completely. However, within the design limitations imposed by these effects some success has been achieved by the method.

3.2.2.4. Icing meters. Another system utilises the fact that supercooled droplets on striking a surface will adhere to it in the form of ice (aircraft icing). In one method a cylinder with its axis normal to the airstream is rotated until it acquires a uniform coating of ice. The thickness of ice deposited in a given time or, alternatively, the amount of water when it is melted, is a measure of the water-content of the amount of air swept through in that time. A development of this method uses a rotating disc in which the thickness of ice acquired per revolution is measured by an electrical transducer. Still another method uses pitot pressure to switch on a heater cyclically as soon as icing blocks up the air holes leading into the pitot tube.

All of these devices work only when supercooled droplets are present, i.e. when the air temperature is below freezing, and moreover they fail at very high values of water-content because the latent heat released on the phase change from water to ice finally raises the instrument-temperature to a point where a considerable proportion of the oncoming water will flow off it rather than freeze. Some success has been achieved in overcoming these difficulties by refrigerating the collection head of the instrument (Ref.20). Fig.16 shows a rotating disc instrument on which this has been done.

3.2.2.5. Results of water-content measurements. The present position is that the general features of water-content distribution in clouds are fairly well known, e.g. it is almost always less than 2 g./m.^{3} in stratiform clouds and does not vary much in time and space. In the centre of cumuliform clouds it may rise to considerably higher values in small areas usually less than a mile across. Within these areas the theoretical maximum value expected from a consideration of the rise of air from cloud base at say 2,000 ft. is about 5 g./m.^{3} at 15,000 ft. in temperate latitudes and 7 g./m.^{3} in the tropics - and present evidence is that these values do in fact occur although the mean over the whole cross-section of the cloud may be only 1-2 g./m.^{3}. When there is sedimentation and heavy rain these concentrations are considerably exceeded in very local areas. However, the data obtained so far are rather sparse and poorly substantiated, and further work is required.

Fig.15 shows some typical results recently obtained in cumuliform and layer clouds with conductivity and heated wire instruments.

3.2.3. Vertical currents and turbulence

Vertical currents in layer-type clouds are seldom more than a few cm. per second and any attempt to measure these by means of the aircraft's motion will fail owing to the comparatively large variations caused by small deviations in

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attitude, aircraft weight, etc. In cumuliform clouds however the prospect is better as vertical motions of 20 or perhaps 30 m./sec. may be found over flight paths of the order of a mile. Thus estimates may be obtained by using the altimeter and airspeed records during a cloud traverse or, alternatively, by integrating a record of the aircraft's vertical acceleration obtained by means of an accelerometer. (Refs.21 and 22). Fig.17 shows a good case from Ref.21.

Many uncertainties may arise due to the effect of the aircraft pitching and assuming a climbing attitude during the traverse but, nevertheless, by examination of these records a good deal of information has been accumulated on the sizes, shapes and magnitudes of up and down currents in these clouds.

Cumuliform clouds are also associated with the most severe turbulence (or bumpiness) encountered by aircraft. The accelerometer records only the aircraft movement at the accelerometer-mounting and the records have to be corrected, where possible, for the lag in the aircraft taking up the air movement and for the elasticity of the aircraft structure. The problem is important in obtaining data for structural design.

3.2.4. Other cloud parameters

Apart from types and sizes of particles, water-content and vertical currents, other parameters, such as the environmental temperatures and humidities, cloud temperatures, concentrations of condensation and freezing nuclei and electrical effects, are important in cloud-physics studies. In addition aircraft observations are also useful in the interpretation of radar reflections from cloud and precipitation and the relation of cloud parameters to the broad synoptic picture, e.g. frontal conditions (Ref.23). Notes on these are now given:

3.2.4.1. Environmental conditions

Mean temperatures can be found simply with any of the aircraft thermometers described above. For fine structure of the thermals rising below cumulus clouds, however, it is often necessary to measure the temperature change in less than 100 feet of aircraft track. A thermometer capable of doing this utilising very fine platinum wires (50 s.w.g.) on an aircraft is available (Ref.24 and Fig.18). Hot wire anemometers can also be used to measure the vertical speed of thermals. From studies with these instruments it has been found that well below clouds thermals are normally a few hundred metres across and rise, in an environment with a dry adiabatic lapse rate, at 1 - 3 m./sec.

Near the cloud base, however, the lapse rate stabilises and the rising air appears to reorganise itself into the larger scale motions found in the clouds. Around cumuliform clouds the atmosphere is characterised by rather smooth flying conditions. There appears to be very little lateral mixing between the cloud and its environment, except perhaps very near the base, and relative humidity is frequently low in the environment.

The cloud-air will tend to rise as long as its buoyancy exceeds that of the environment. If we compute the buoyancy of the air in the cloud on the assumption that the suspended water at a given level is supported by the surrounding air it appears that for typical cumulus clouds in these latitudes:-

(a) The cloud-air will often have positive buoyancy up to heights of about 10,000 feet, even if the cloud-air temperature does not materially exceed the environmental temperature. If the humidity of the environment is very low near cloud base it may even be possible for the cloud temperature to be less than the temperature of the surrounding clear air and positive buoyancy still to exist.

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(b) At high levels, say 20,000 to 30,000 feet, the effect of the suspended water in concentrations of about 4 or 5 g./m.^{3} becomes very important. The cloud temperature will have then to exceed the environment temperature by 3 or 4°F to maintain positive buoyancy. When a level is reached where the cloud temperature excess is not sufficient to do this the updraughts begin to decelerate and finally the cloud top will occur when friction forces bring the vertical currents to a standstill. There are several theories concerning the nature of the processes of updraughts and the heights reached by the tops of cumulus clouds, and these could be improved if accurate data on cloud temperatures were available.

3.2.4.2. The measurement of cloud temperature

In general aircraft thermometers will record temperatures in cloud which are low compared to those recorded outside the cloud. This is because of the evaporation, due to kinetic heating, of water collected on their surfaces, the magnitude of the effect being governed by the proportion of the thermometer surface which becomes wet. If ice forms on the surface of the element the release of latent heat of sublimation will also affect the readings and tend to make them too high. In all but the worst conditions, however, experience has shown that the flat plate type of element is not affected to a great extent by icing effects and also that its readings, corrected empirically for the wetting of the element at temperatures above freezing, will only be a few degrees in error. This error, although not appreciable for many applications, may be serious when the buoyancy of a cloud mass has to be estimated and efforts have been made to improve the accuracy by shielding the element from wetting and particularly from the effects of icing. Unfortunately, although this does bring about some improvement the shield itself will normally tend to become wet and air in contact with it cooled by evaporation, so that it is likely that the thermometer will still read low. Whether or not this is the true explanation, practical tests with vortex thermometers have given low readings even when it appeared that there was little chance of the element itself becoming wet. Alternative explanations, based on the idea that droplets evaporate in the air and thereby cool it as they approach an obstacle, hardly seem feasible in view of the comparatively large time needed to evaporate a droplet compared with the time it is in the vicinity of the thermometer element. At the present time the vortex thermometer probably gives the most reliable readings in cloud, although other types are available in which the element is shielded. At temperatures above freezing point a wet-bulb thermometer may be used: its advantage is that, as the whole bulb is covered with water, the effect of evaporation is less variable than in the case of a thermometer which is only incidentally wetted by its passage through the cloud. Some success has been achieved in this way in studies of cumulus clouds in trade winds (Ref.25).

3.2.4.3. The use of radar for cloud physics studies

In this country the Meteorological Office operates a ground radar station at East Hill, near Dunstable, and aircraft in radio communication with this station have been directed into regions giving radar echoes from cloud and precipitation, with the object of linking the radar reflection with the size and nature of the cloud particles and other cloud parameters. Studies of this type present many operational difficulties in this country as the height, position and course of the aircraft are severely limited by Air Traffic Regulations. A series of results linking radar and aircraft observations has been produced by Jones (Ref.26) and it is likely, with the improved methods of particle sampling recently developed, that it will be possible to extend this work considerably.

An alternative method, already used in America and Australia, and also for icing research in this country, is for the aircraft to carry radar equipment in its nose and for radar observations of the cloud to be taken while the cloud is being approached before a traverse. This has the advantage that the observations can be co-ordinated more readily and also that the state of the cloud as regards precipitation can be estimated without actually traversing it.

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On the other hand, the instrumental equipment of an aircraft engaged in cloud physics work is already very large without the complication of the airborne radar equipment, the inclusion of which adds considerably to the technological problems of the operator.

3.3. Cooperation with other meteorological research sections

It is, of course, not difficult to combine the research effort of a meteorological flight with that of other research sections both as regards the macroscopic aspects of cloud studies and other phenomena. In this connection, apart from the work on jet streams mentioned above, studies of lee waves from mountains and of the conditions for dissipation of stratocumulus cloud are in hand at present. Other fields in which this type of cooperation is carried out include studies of radiation and diffusion discussed below and, in collaboration with the Forecast Research Division at Dunstable, of the structure of frontal cloud systems. Fig.19 shows a typical section of a frontal surface obtained during this work.

3.4. Atmospheric nuclei

One of the most active fields of research, in which considerable progress has been made over the last two decades, is the study of nuclei in the atmosphere. Such nuclei effectively range in diameter from about 10^{-7} to 10 microns in cloud physics studies, and their investigation requires the measurement of their sizes, shape and chemical composition as well as of their ability to act as condensation or freezing nuclei. Information of their distribution in time and space (particularly altitude) is also required. Recent studies using aircraft for some of these purposes in this country are outlined below:

3.4.1. Condensation nuclei

For many years the study of condensation nuclei on the ground has been carried out using the Aitken nucleus counter or some variant of it. This instrument has also been used in aircraft in America but it was found at the Meteorological Research Flight that the instrument designed by Pollak (Ref.27) was more suitable for aircraft use. (Fig.20). The results of flights with this instrument have been presented by G.J. Day (Ref.28). It was found in flights over the sea that clean maritime air contains in the order of 10^2 to 10^3 condensation nuclei per cc., but that over the land the concentration is usually about an order more and, near to certain industrial sources, considerably higher. In general, concentration fell off considerably with height, the vertical distribution being dependent on the atmospheric stability. Concentration varied considerably with location, as illustrated in Fig.22 which shows the measurements taken in a flight round England.

3.4.2. Freezing nuclei

The concentration of freezing nuclei in the atmosphere can be determined by means of the "cold box" and work using this apparatus has been described by E.J. Smith and K.J. Heffernan of the Commonwealth Scientific and Industrial Research Organisation, Australia (Ref.29). A similar installation is in use in the Meteorological Research Flight (Fig.21). A cylindrical chamber of about 60 litres capacity is cooled by pumping methylated spirits round a circuit which includes pipes wound round the cylinder and a copper spiral immersed in solid carbon dioxide. Steam is introduced into the chamber by means of a small boiler, the chamber is strongly illuminated and the light beam viewed at right angles. The water droplets appear as a dull opaque fog but any ice crystals which appear sparkle and glisten. The estimation of the number of ice crystals is subjective, but by measuring the temperature at which they appear in recognisable quantities, some idea can be formed of the temperature at which any freezing nuclei present become active. It is found that in general the ice crystals are very few down to -20°C or so when the number usually increases markedly. Even so, the concentration is only

of the order of 10 to 10^4 per litre, which is small compared to the number of condensation nuclei at low levels. It appears on the whole that ice nuclei do not decrease in numbers with increasing height in the same manner as condensation nuclei and it may be that they are of extra-terrestrial origin. Fig.23 shows some recent results of the variation of freezing nuclei concentrations from day to day in January, 1956.

3.4.3. Salt nuclei and the determination of the chemical constitution of nuclei

Various techniques exist for the sampling of salt nuclei and their chemical determination. Both in Australia and the U.S.A. particles have been captured on hydrophobic surfaces and examined microscopically under conditions of varying humidity (Refs.30 and 31). Their distribution in relation to the wind and to the distance from the sea allows an estimate to be made of the possible concentrations of these particles available for initiating the coalescence mechanism of rainfall in different localities. It has been found, for instance, that over the sea rather small clouds with tops well below the freezing level will produce rain, while much larger clouds in the centre of land masses fail to do so, and one possible explanation of this is the relative availability of large hygroscopic nuclei.

Chemical determinations of nuclei can be made by the Liesegang ring or similar techniques (Ref.32). An impactor of the type designed for the diffusion studies described below may be used to project an airstream on to a specially prepared surface consisting of a gelatine impregnated with a soluble salt chosen to give a suitable reaction with the radical to be sampled. An impinging nucleus will react to produce an insoluble characteristic deposit which may be examined under a microscope at leisure. For instance, when one is attempting to sample chloride the agent may be a soluble silver salt, and the deposit to be examined will be the insoluble silver chloride, which can also be reduced to metallic silver.

Other techniques for sampling small particles are available, and it is probable that this aspect of the work will receive more and more attention as the subject develops. One application of small-particle sampling which has recently been used in the U.S.A. and in this country (Refs.33 and 34) is concerned with the study of medium- and long-range diffusion of particles.

3.4.4. Diffusion studies and their application to rain-making experiments

It is important for some purposes to be able to predict the concentrations at given heights and distances downwind of particles released from a ground source, and data of this type are also required for fundamental studies of diffusion processes. An obvious practical application is the release of silver iodide particles from surface generators in the hope that they will be carried up into the air and act as freezing nuclei, thereby modifying the composition of clouds and perhaps producing greater rainfall. The physical processes involved are not at present thoroughly understood so that work is being carried out both on the fundamental physics of rain-producing processes and practically, by a series of experiments involving large scale release of silver iodide into cloud systems, followed by a statistical analysis of the rainfall downwind compared with that falling in nearby control areas. An obvious prerequisite of the process is that the silver iodide particles reach a height at which they can be effective within a reasonable time. Unfortunately it is difficult to sample silver iodide particles in the air, and detailed work from aircraft both in this country and the U.S.A. has usually been carried out with zinc sulphide particles of sizes 0.5μ to 3μ diameter. These particles fluoresce characteristically when illuminated by ultra-violet light and hence can easily be counted once they are sampled by an impactor in the aircraft. Fig.24 shows the type of impactor used. Air is sucked through the nozzle on to a suitably prepared surface of a drum. The drum is rotated in three-degree steps by an actuator, so that 120 samples can be obtained on it, each for example corresponding to one minute, or say, 3 miles of flight. Course,

/height,

height, direction and location are also noted for each sample and it is possible to relate concentrations in the plume of material to other factors such as lapse rate, wind speed, etc.

The preliminary results of this work show that the plume, up to any level, normally travels at the speed and in the direction of the mean wind from the surface to that level and also that the particles do not penetrate through sizeable inversions. Mean plume widths are variable and rapidly exceed their heights. They may subtend an angle at the release point of as much as 40° at distances of 5 miles or so from the source but only about 20° at 40 miles from it. The distribution has much the same form at all heights.

Because of the variability of the results and the many conditions in which the information is needed, considerably more data are required before reliable empirical formulae for concentrations at any point can be derived or a worthwhile agreement with theory obtained. In particular it is hoped to extend the sampling work to frontal-cloud conditions. Modifications of the impactor system are being devised to allow sampling to be carried out in clouds and rain.

3.5. Other aspects of cloud modification

Apart from cooperation in experiments on large-scale rain-making, aircraft have been used in many countries in small-scale trials for modifying cloud. Either a nucleating agent such as silver iodide is used, or, more commonly, solid carbon dioxide is dropped into super-cooled clouds with the object of converting the droplets into ice crystals. Work of this type on cumuliform clouds is often not very satisfactory, as this type of cloud changes so rapidly that it is not always possible to ascertain whether the cloud has in fact been modified by the operation. For successful scientific experiments of this type observations other than those of a single aircraft, e.g. radar photographs of the cloud, a second observing aircraft and ground observers, are necessary before it can be stated with any authority that the subsequent changes in the cloud have been induced by the seeding. Even when these are available it is not always possible to be sure. Similar remarks also apply when attempts are made to induce precipitation by the coalescence mechanism by introducing water drops or salt nuclei into the base of a cumulus cloud.

Supercooled layer clouds however can be modified with certainty and the process of modification followed and examined. Figs.25 and 26 show pictures taken during experiments of this type carried out on 9.1.56 and 23.1.56 respectively. Other similar work by the Meteorological Research Flight has been described in Refs.35 and 36. The plan of these experiments was to make measurements in the layer to be seeded, e.g. water content, drop size, etc., when possible, and lapse rates of temperature above and below the cloud, and then to drop about 100 lb. of dry ice in the form of small pellets into the cloud at the rate of 3 to 10 lb./mile of flight. The presence of water cloud was revealed either by icing of the aircraft when flying in it or by the presence of a "glory" around the shadow of the aircraft on the cloud when flying above it. After seeding, the aircraft usually ascended a few thousand feet above the cloud to a convenient height from which to take photographs. For a cloud several thousand feet thick about 15-20 minutes elapse before anything is seen. Then the seeded area takes on a characteristic opaque appearance and precipitation patterns of a similar shape may be observed on the screen of a ground radar station. A little later the cloud in the seeded area disperses, leaving a hole which slowly enlarges. Sun pillars may appear, formed by reflection of the sun's rays from ice crystals at the edges of the surrounding cloud. There may also be slight cumuliform growth around the edge of the hole, which is reflected in a local increase in water content if measurements are made during an aircraft traverse across it.

The practical value of these experiments is however limited. In favourable conditions, areas of perhaps 10 to 15 square miles in a cloud 2,000 feet

thick may be cleared by using about 100 lb. of dry ice. However the whole process takes between 40 minutes and an hour, and during that time the seeded area may drift 20 or 30 miles, so that any operational work based on it would be difficult to plan. Moreover, the occasions when these experiments can be carried out in the United Kingdom are few. In Southern England large areas of supercooled stratocumulus usually only occur during the winter months during periods of easterly winds.

3.6. Radiation measurements from aircraft

Many of the current uncertainties in our knowledge of solar and terrestrial radiation can be resolved by carrying suitable instruments on aircraft. Attempts have been made to carry out infra-red spectroscopy in the stratosphere, since most of the absorption is in the lower troposphere (Ref.37) and this work is continuing. Extensive aircraft observations are required of the albedo of clouds and haze as well as that of different land and sea surfaces before the total albedo of the earth can be estimated. In conjunction with Kew Observatory a start has been made on some of these aspects by carrying two solarimeters, one below and the other on top of the main fuselage of the aircraft. Preliminary results for these measurements give values of 0.06 to 0.07 for the albedo of sea surfaces and 0.1 to 0.3 for land (0.8 when snow covered). For water clouds the values are extremely variable, depending on depth, water content and possibly particle size, while thin ice clouds show little more effect than would be anticipated from their saturated water vapour content. Absorption by water cloud usually appears to be in the region 10 - 20% although theoretical studies suggest rather smaller values. Fig.27 shows a typical result from this type of flight (Ref.38).

A parallel series of experiments has been made measuring infra-red radiation at night using instruments (Fig.28) described by J.T. Houghton and A.W. Brewer in Ref.39. A typical result from these flights is shown in Fig.29 in which simultaneously measured temperatures, frost points, and incoming and outgoing radiation values are compared. Using these data Houghton (Ref.40) has been able to check the results of computations made by means of radiation charts of the upward and downward flux of radiation at high levels as well as to provide information on the emissivity of various surfaces and specified clouds. The value of this work for measurements in the stratosphere is at present limited by the range to which the instruments can extend into the infra-red region. As further improvements are made in instruments of this type, however, it should be possible to accumulate more data on radiation in the stratosphere.

4. Concluding remarks

Although the review above has covered somewhat sketchily a large variety of subjects which are of particular interest at present to the Meteorological Research Flight it has by no means exhausted the applications of aircraft to investigations of atmospheric phenomena. Notable omissions include electrical and magnetic measurements, especially such interesting features as charge distribution in thunderstorms, conductivity and ion content of the air, etc., and investigations of radio-activity which, although perhaps not pure meteorological research, are allied subjects.

The multiplicity of the problems, their separate difficulties of instrumentation, observation and, in particular, reduction of the data, create serious problems of subject priority and allocation of manpower for those directing the use of the aircraft resources. Once aircraft become allocated for general research work they must, for economic reasons, be used as far as possible to the limit of their flying capacity and this must be also an extremely important factor in determining the particular fields to be investigated. It also means that there is often room for University staffs to make use of the flying facilities in allied researches provided their experiments can be satisfactorily combined in the flying programme of the official organisation. It is certainly advantageous, in a subject such as meteorology where there is so much to investigate, to have the aircraft always available for many purposes rather than to

/obtain

obtain them specially for a limited research on a particular subject, and there are signs that other countries are now contemplating setting up similar organisations.

As regards the future, the tendency will be for the aircraft to be flown to greater altitudes and at greater speeds, and for the observations to be extended to other latitudes. At the same time, methods will become more refined and involve more advanced technology. At the highest altitudes we may expect the techniques of measurement to be intermediate between those used in present-day aircraft and those used in rockets for research in the upper atmosphere, with a greater emphasis on remotely controlled and automatically recorded measurements. Near the surface the emphasis will probably change gradually towards measurement of smaller-scale phenomena, with concentration on small lag and greater rapidity in measurement and recording, and the improvement of the experimental procedure as a whole to a standard comparable with that attainable on the ground.

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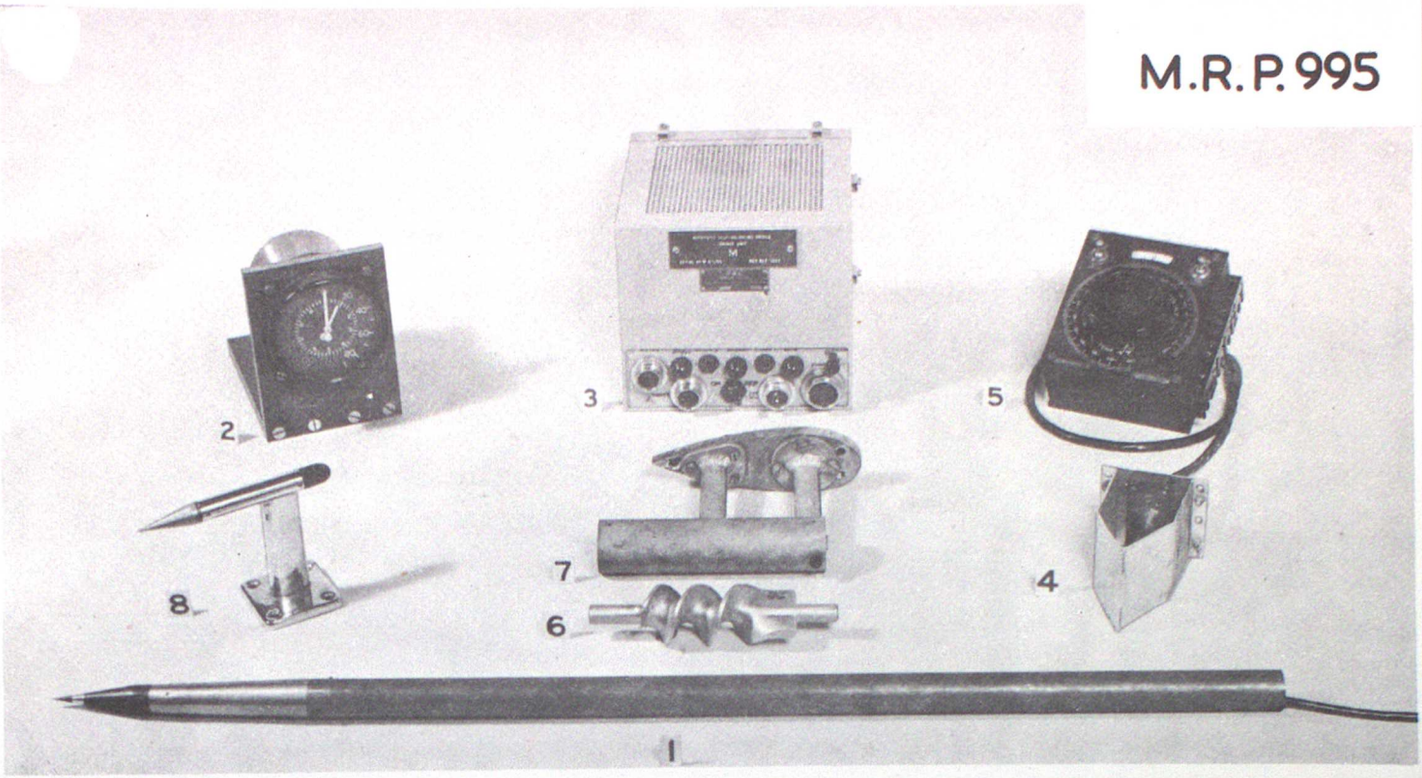


FIG.1 AIRCRAFT THERMOMETERS

(1) Experimental Conical Head type (Meteorological Office, Harrow). This is mounted ahead of a wing tip or fuselage nose. The element is a platinum resistance in the cone.

(2) Dial for (1) operated through (3).

(3) Self balancing resistance bridge controlled by (1) with output presentation on (2).

(4) Meteorological Office Flat Plate Aircraft Thermometer.

(5) Hand operated bridge, reading temperature when balanced to resistance of (4).

(6) Internal spiral to transform linear airflow into Vortex in the Axial type of Vortex Thermometer.

(7) External view of Vortex Thermometer.

(8) M.R.F. Conical Type Aircraft Thermometer for under wing or under fuselage mounting.

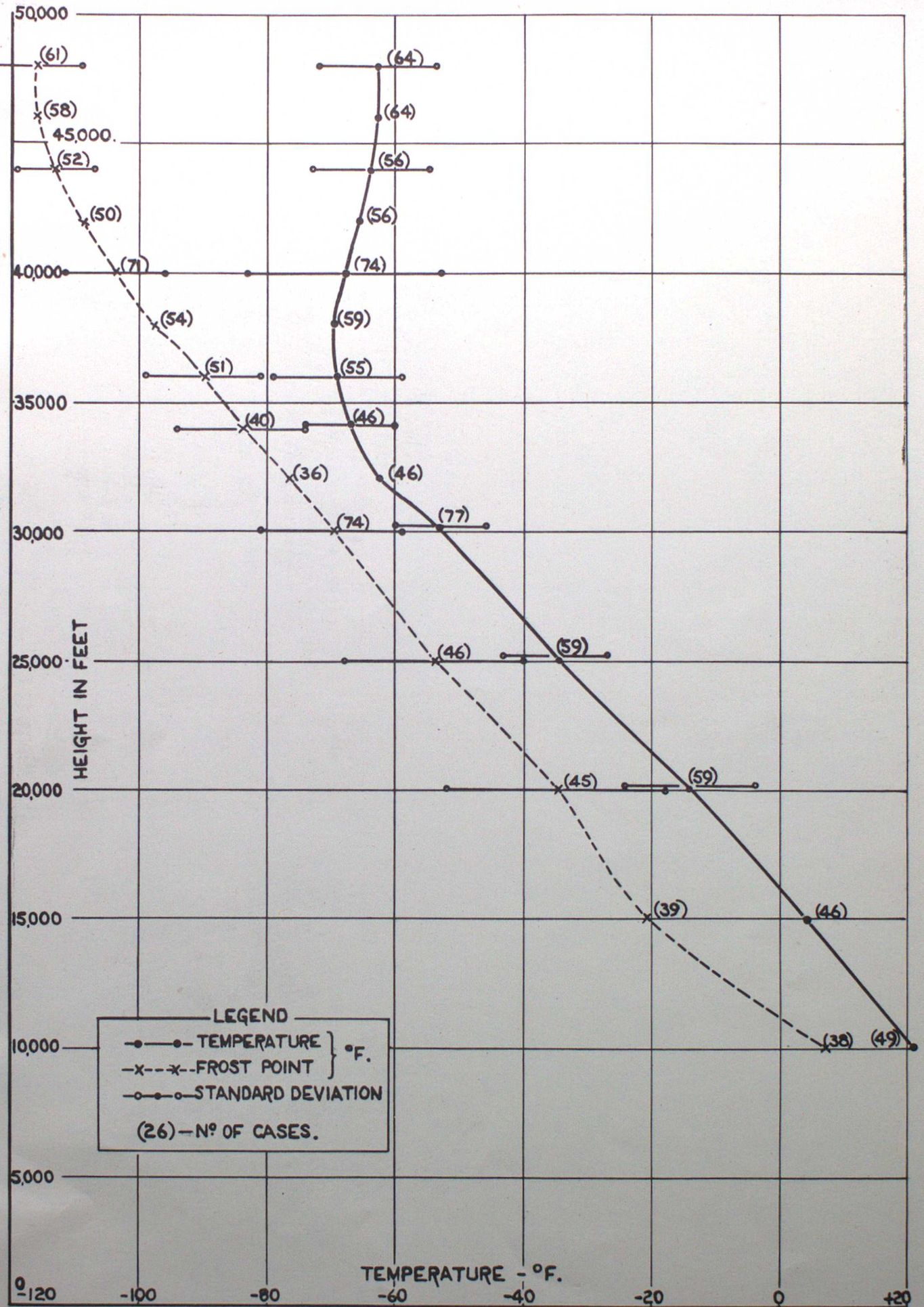
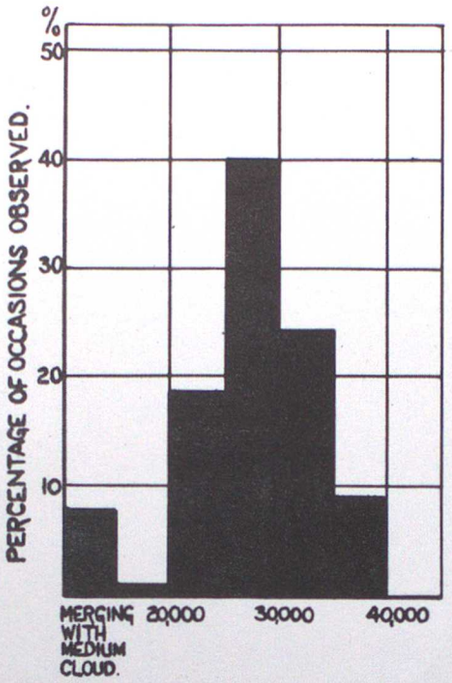
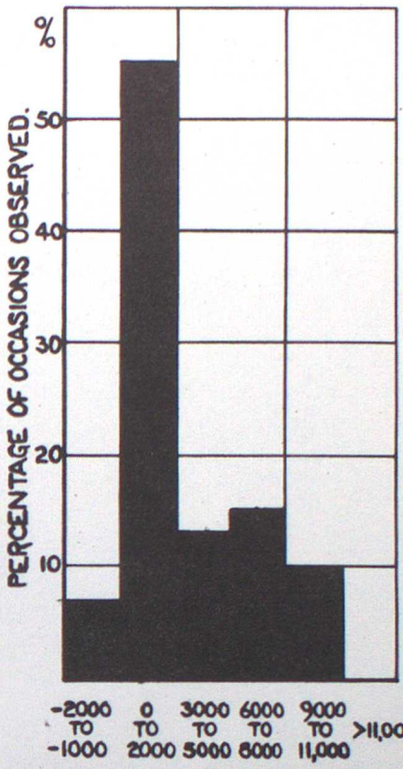


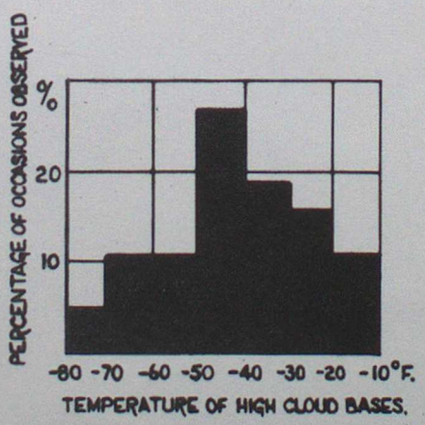
FIG.2. TEMPERATURE AND FROST POINT OVER SOUTHERN ENGLAND (81 ASCENTS FOR 1954 AND 1955.)



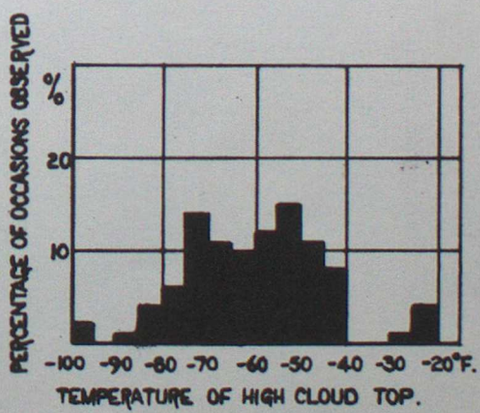
FREQUENCY DISTRIBUTION OF THE HEIGHT OF THE CIRRUS BASE. Nº OF OBSERVATIONS = 63.



FREQUENCY DISTRIBUTION OF THE DIFFERENCE BETWEEN THE HEIGHT OF THE TROPOPAUSE AND THE HEIGHT OF THE CIRRUS CLOUD TOPS. Nº OF OBSERVATIONS = 78.

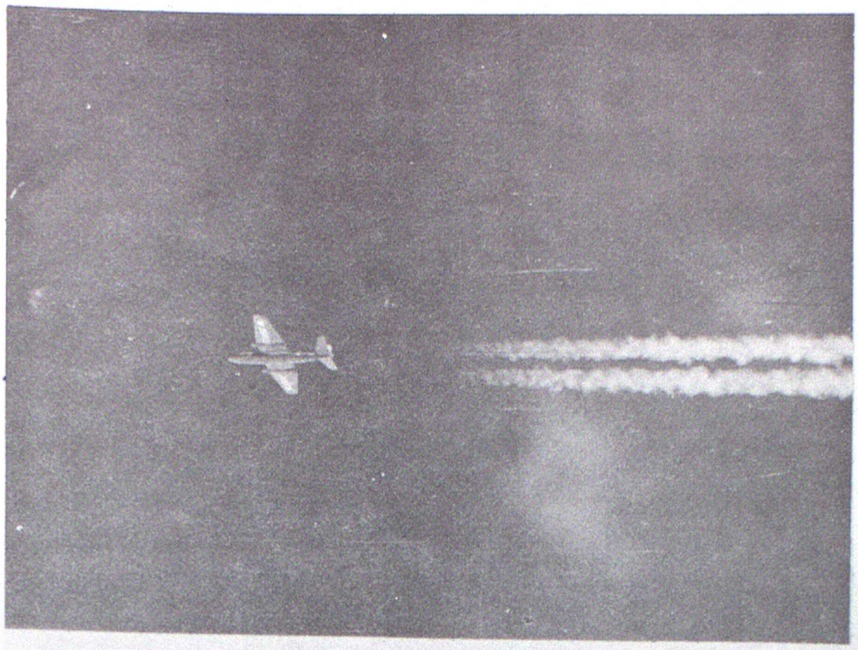


FREQUENCY DISTRIBUTION OF THE TEMPERATURE OF THE BASE OF CIRRUS CLOUD. Nº OF OBSERVATIONS = 63.



FREQUENCY DISTRIBUTION OF THE TEMPERATURE OF THE TOPS OF CIRRUS CLOUD. Nº OF OBSERVATIONS = 81.

FIG.3 OCCURRENCE OF HIGH CLOUD OVER SOUTHERN ENGLAND.



(a)

(c)

(d)

(b)

(e)

FIG.4 CANBERRA AIRCRAFT CONDENSATION TRAILS

(a) Showing gap between aircraft and trail.

(b) Close-up.

(c),(d),(e) Photographs taken with camera looking backwards from the aircraft tail, showing trails from each engine merging in the distance.

(c) and (d) Short trails above large cumuliform clouds.

(e) Long persistent trail.

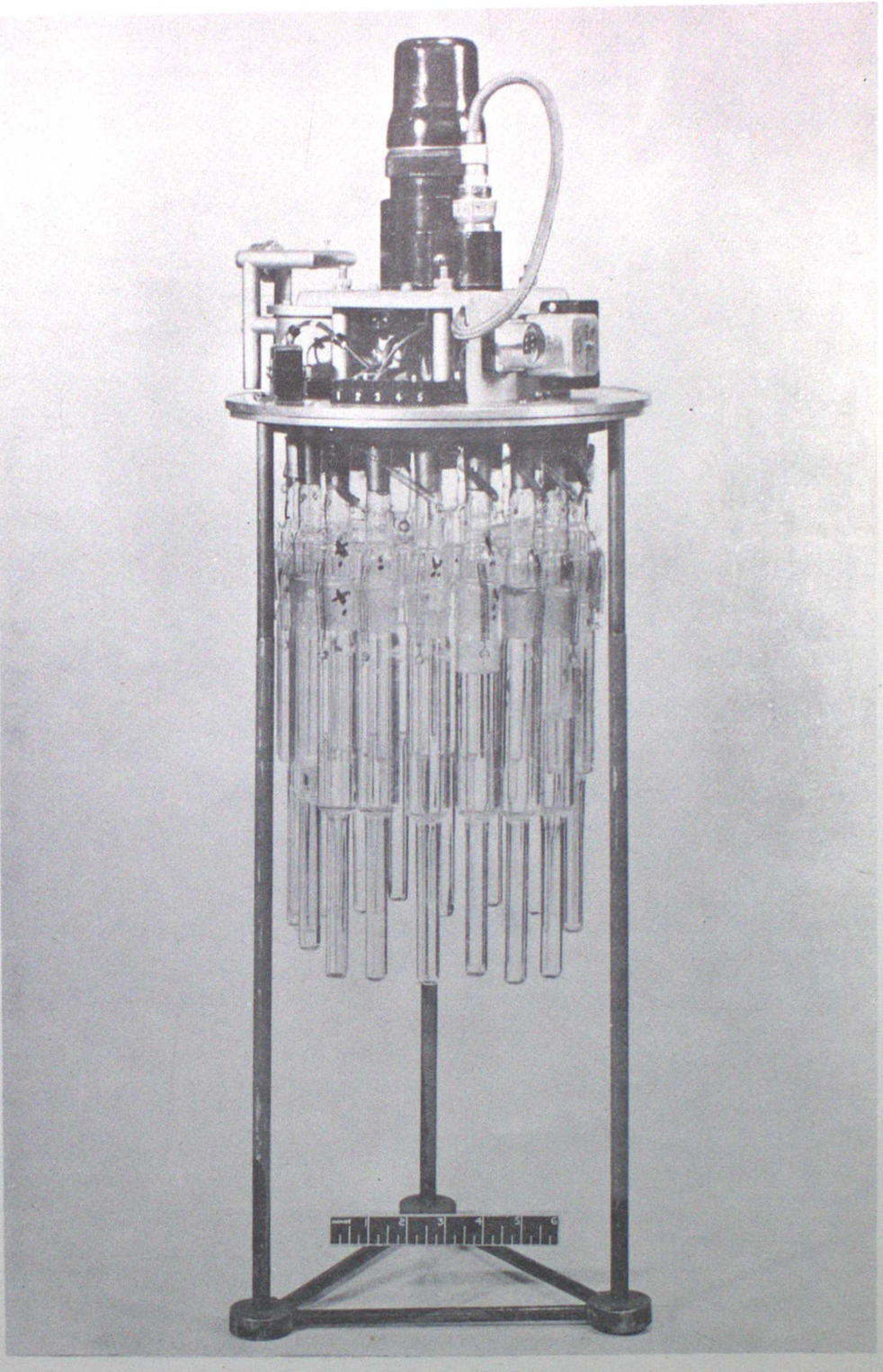


FIG.5 AIRBORNE OZONE SAMPLING APPARATUS

After going through a control valve the air is passed through a selected test tube. Selection of the test tubes is controlled electrically from the observer's seat by means of the actuator mounted above the tubes. This part of the apparatus is located in the bomb bay and the test tubes are loaded before each flight and withdrawn afterwards for analysis.

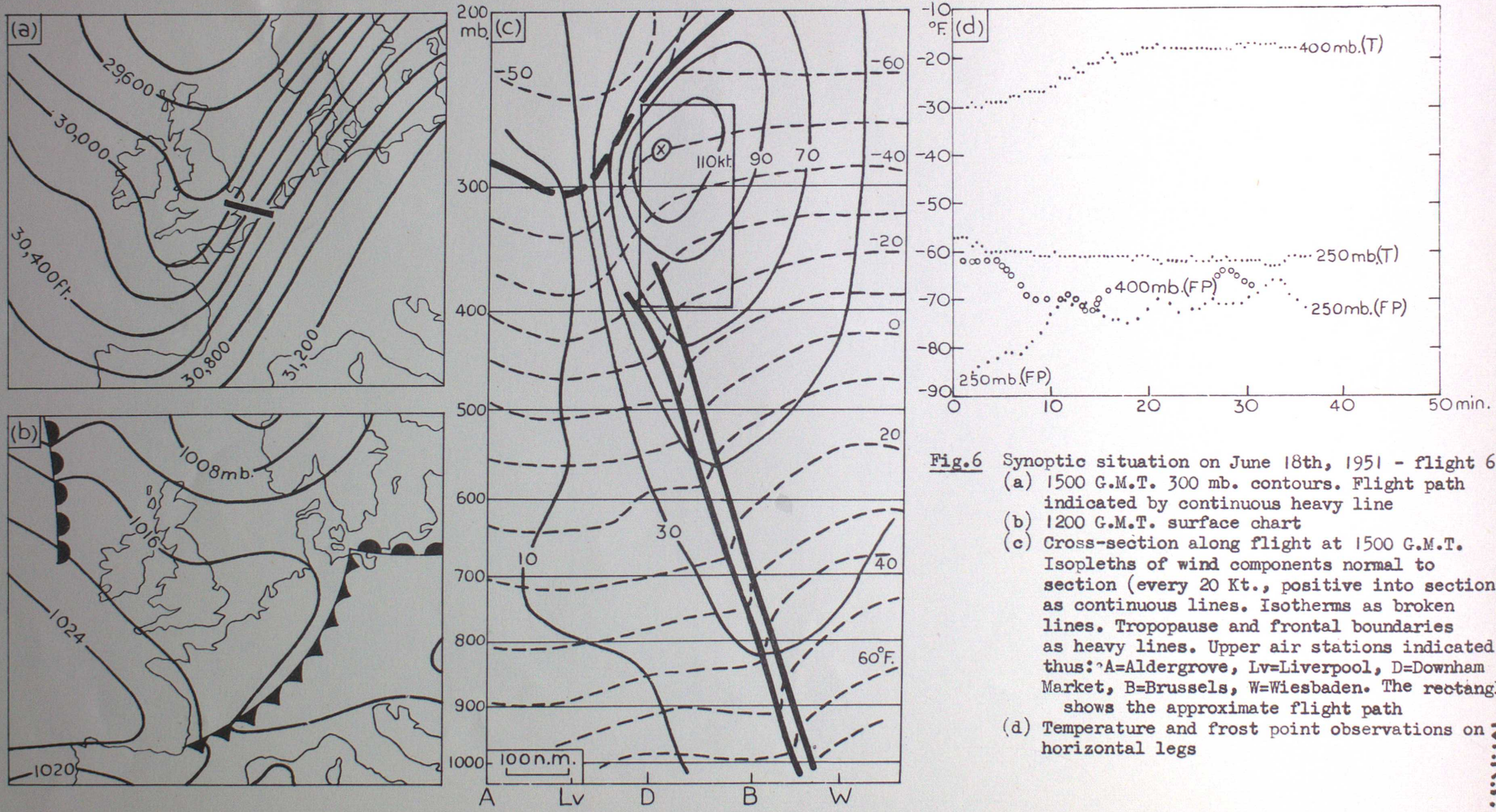


Fig.6 Synoptic situation on June 18th, 1951 - flight 6.
(a) 1500 G.M.T. 300 mb. contours. Flight path indicated by continuous heavy line
(b) 1200 G.M.T. surface chart
(c) Cross-section along flight at 1500 G.M.T. Isopleths of wind components normal to section (every 20 Kt., positive into section) as continuous lines. Isotherms as broken lines. Tropopause and frontal boundaries as heavy lines. Upper air stations indicated thus: A=Aldergrove, Lv=Liverpool, D=Downham Market, B=Brussels, W=Wiesbaden. The rectangle shows the approximate flight path
(d) Temperature and frost point observations on horizontal legs

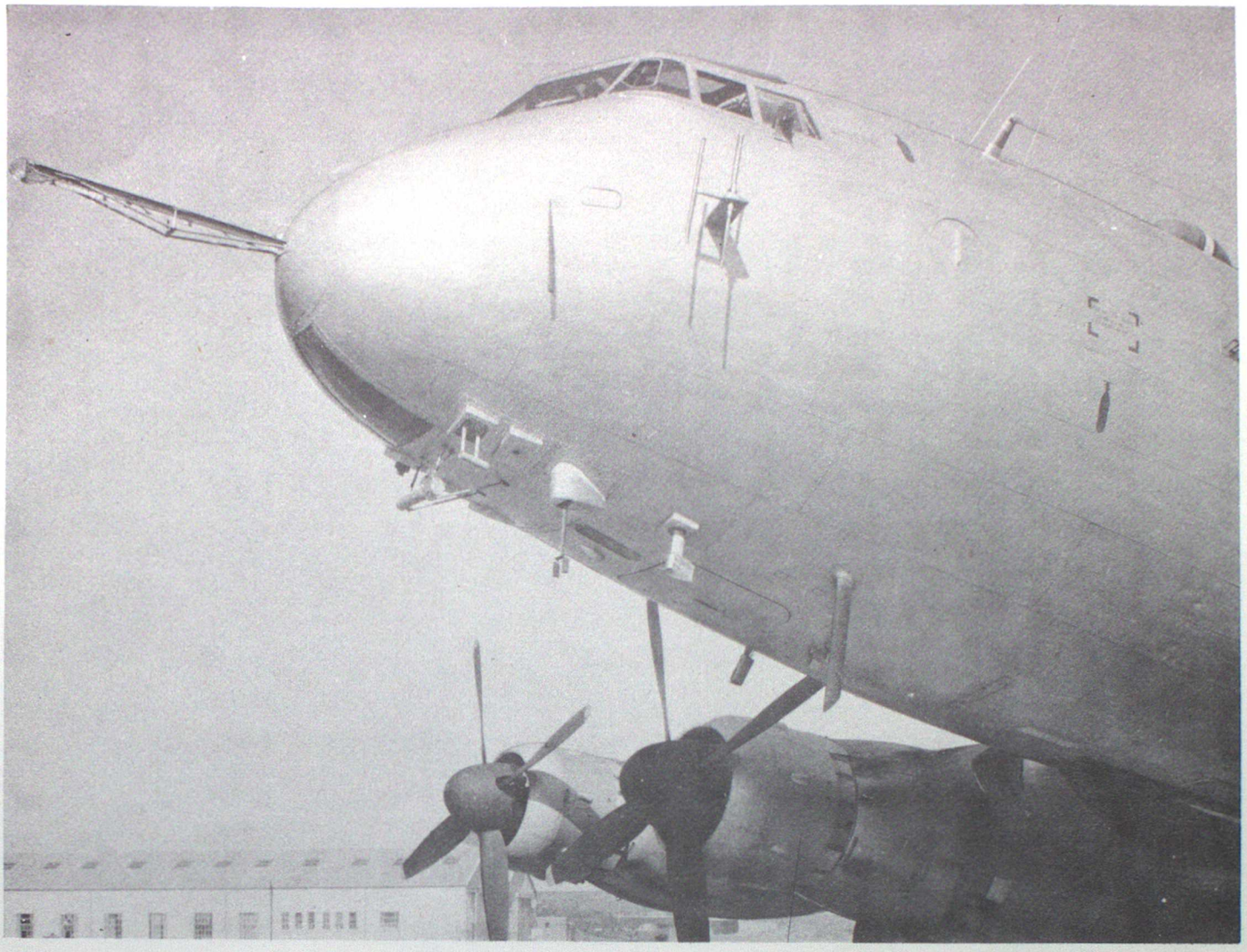


FIG.7 EXTERIOR OF HASTINGS AIRCRAFT

A variety of instruments are mounted forward of, and under the nose. Mountings are provided for easy removal and replacement and, where necessary, instruments can be retracted into interior.

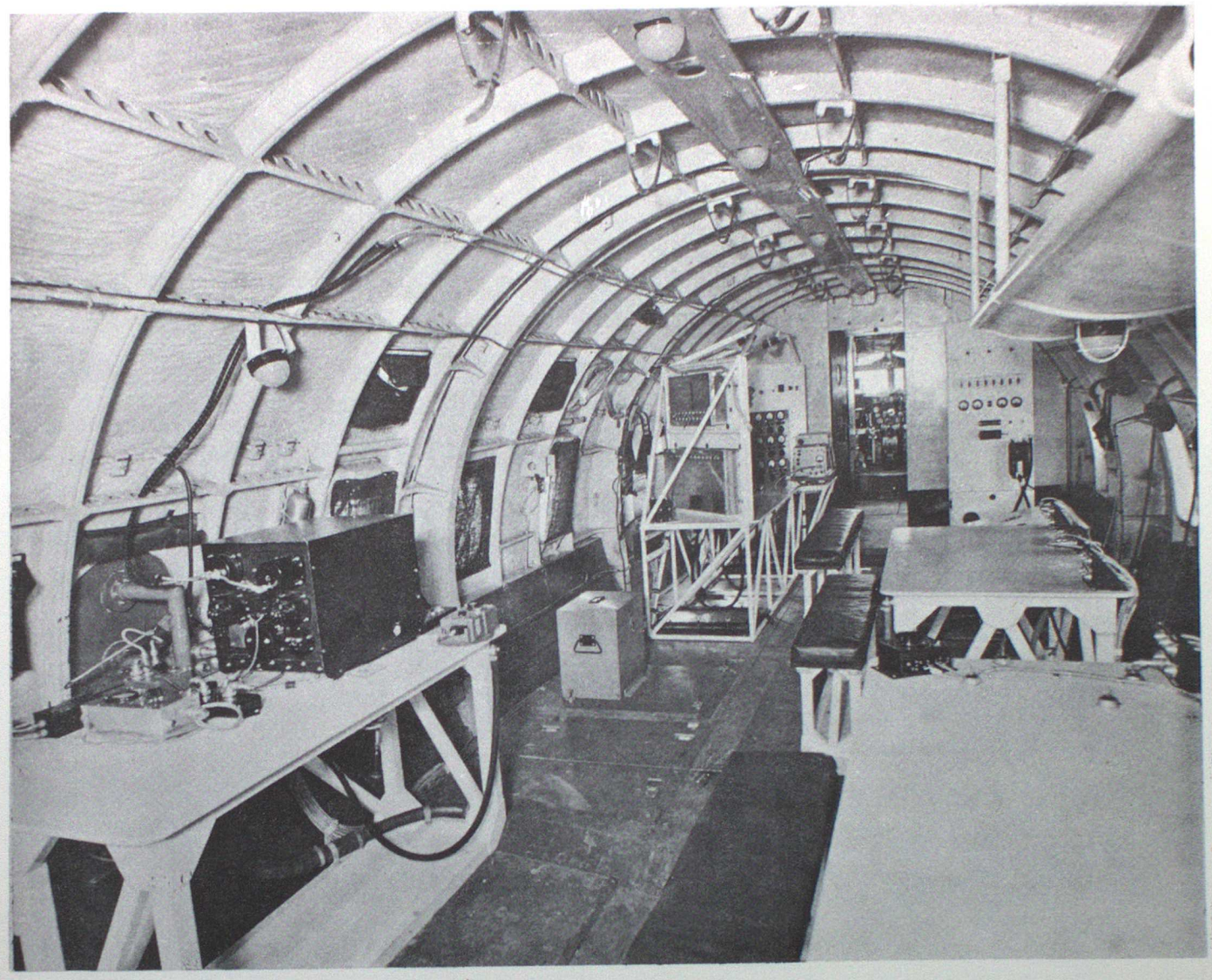


FIG.8 INTERIOR OF HASTINGS AIRCRAFT

This has been rebuilt to provide laboratory conditions of work as far as possible.

Each bench is provided with several plug positions for different power supplies and connections to instrument heads.

In Left Foreground is an Automatic Observer.

Left Rear is the multichannel galvanometer equipment.

Right Rear is the power board for the experimental equipment.

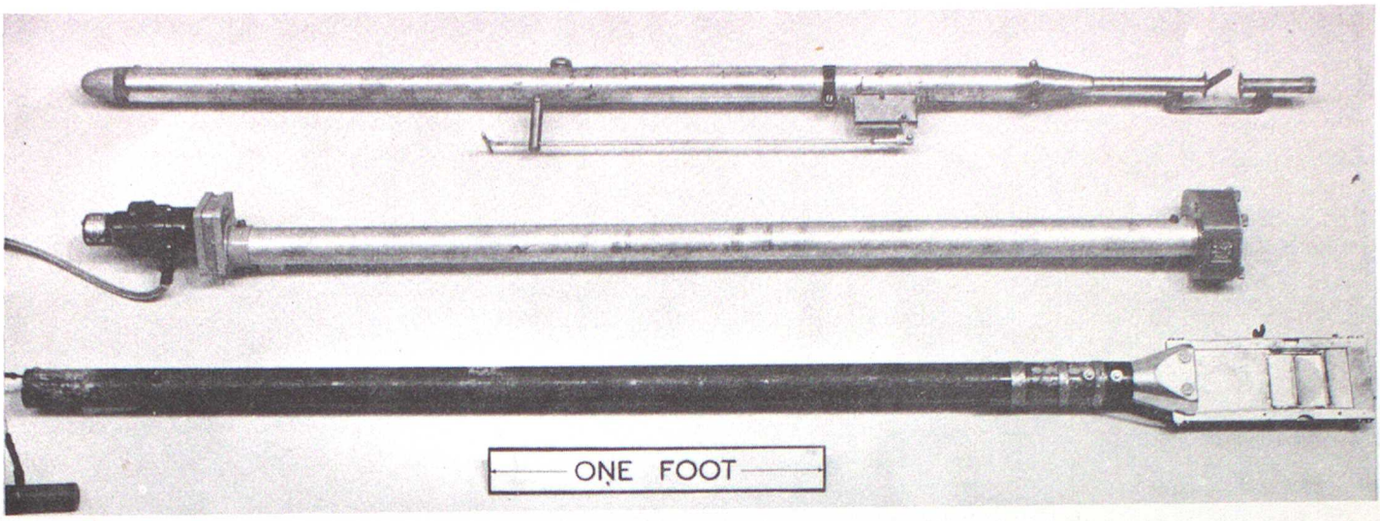


FIG.9 PARTICLE SAMPLERS

TOP: CLOUD DROPLET TYPE. Slide is oiled and placed in holder between bell mouths. (So shaped to avoid splash effect on the slide.) Slide is fired across the gap by means of trigger arrangement below, immediately the sampler is pushed out of the aircraft.

(This impactor was adapted from a design by D. Napier & Sons Ltd.)

CENTRE: RAINDROP SAMPLER. Small electric motor on the left drives drums in the head on the right. Tinfoil strip is run at about 4 inches per second, under the opening in the head, and suffers indentations by oncoming raindrops, thus producing a continuous record of raindrop size.

BOTTOM: RAINDROP SAMPLER USING SOOTED GAUZE METHOD. Gauze is placed in the holder on the right and is exposed by manually operating a shutter from the left.

All these samplers are exposed by mounting on a ramp and pushing through a hole in the aircraft skin, as shown in FIG.10.

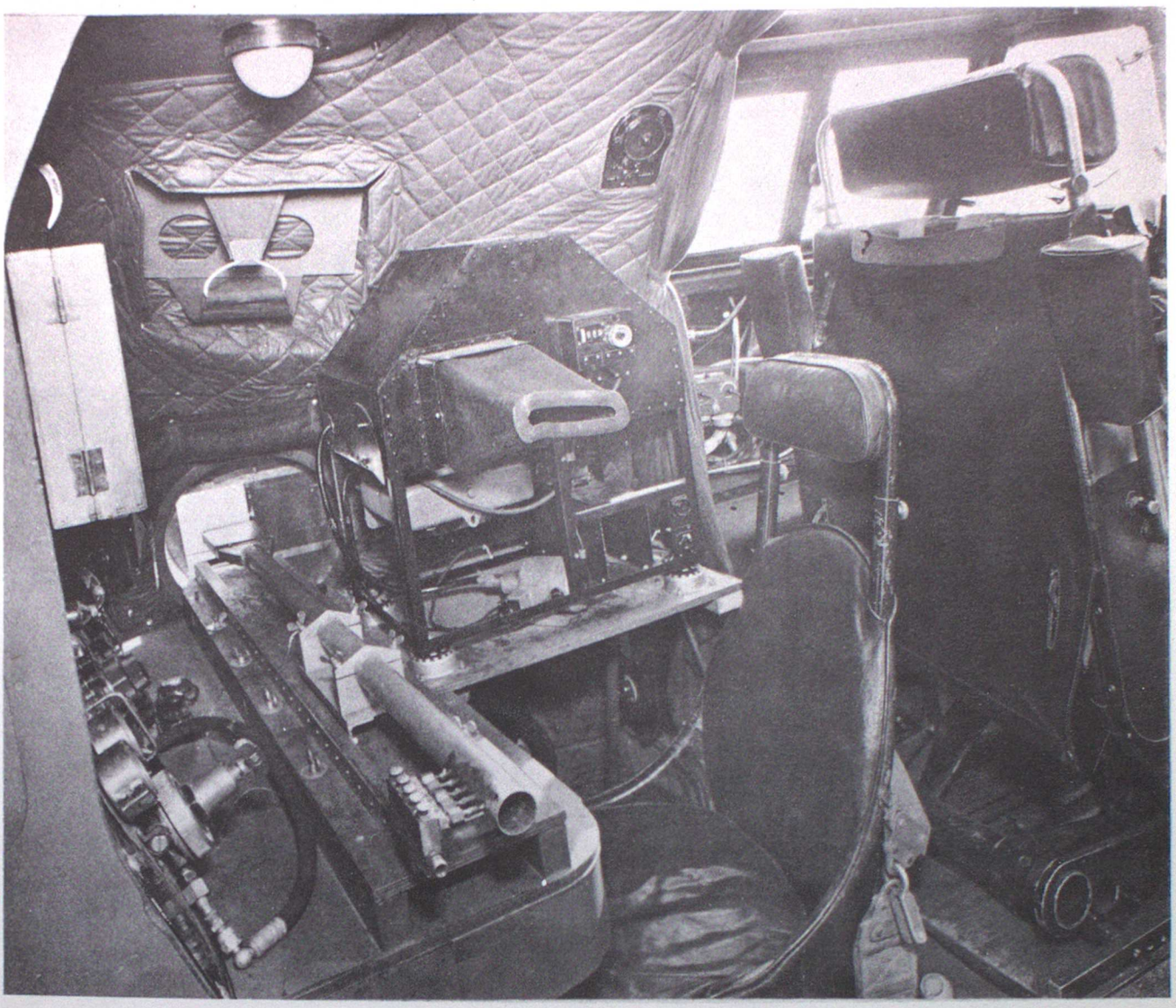
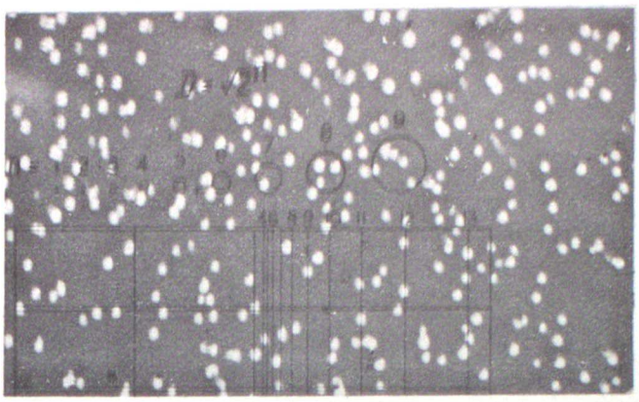


FIG. 10

Illustrates method of exposing samples through aircraft skin by means of sliding ramp.

Droplet samples are photographed immediately, in the micro-camera to the right of the operator's seat.



(a)

(b)

FIG. 11 TYPICAL CLOUD DROPLET SAMPLES

(Mean diameter approximately 20 microns)

(a) Craters in coating of Magnesium Oxide.

(b) Droplets captured in oil.

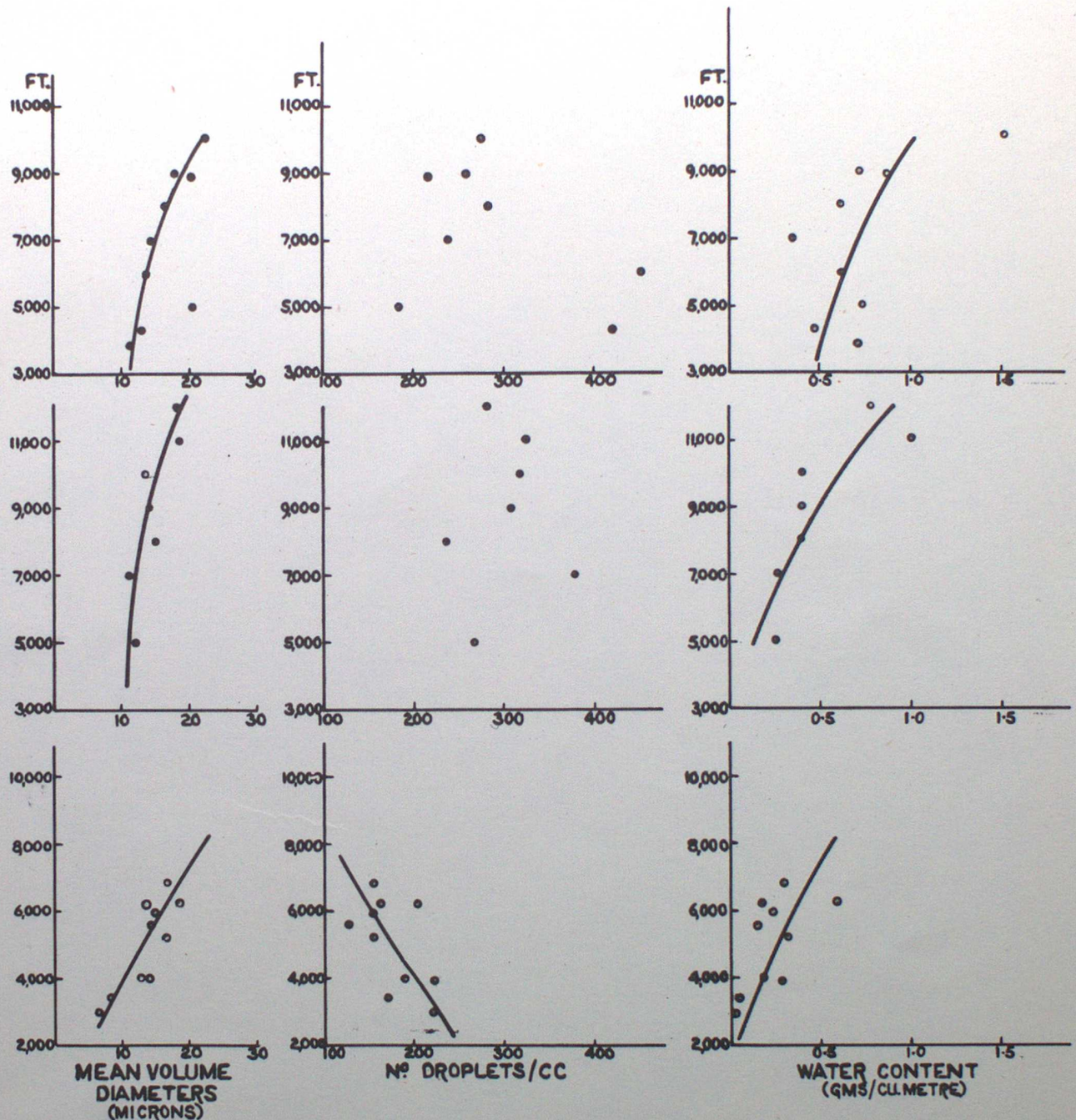
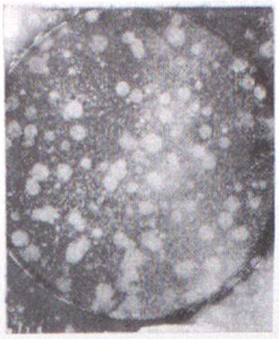


FIG. 12. VARIATION OF DROPLET SIZE AND CONCENTRATION IN CUMULUS CLOUDS. (THREE SEPARATE FLIGHTS).



(a).... LARGE DROPS WITH SOOTED GAUZE.

(b).... SNOW FLAKES WITH SOOTED GAUZE.

(c).... SMALL DROPS WITH SOOTED PLATE.

FIG.13 RAINDROP AND SNOWFLAKE SAMPLING WITH SOOTED SLIDES
(Approximately original size)

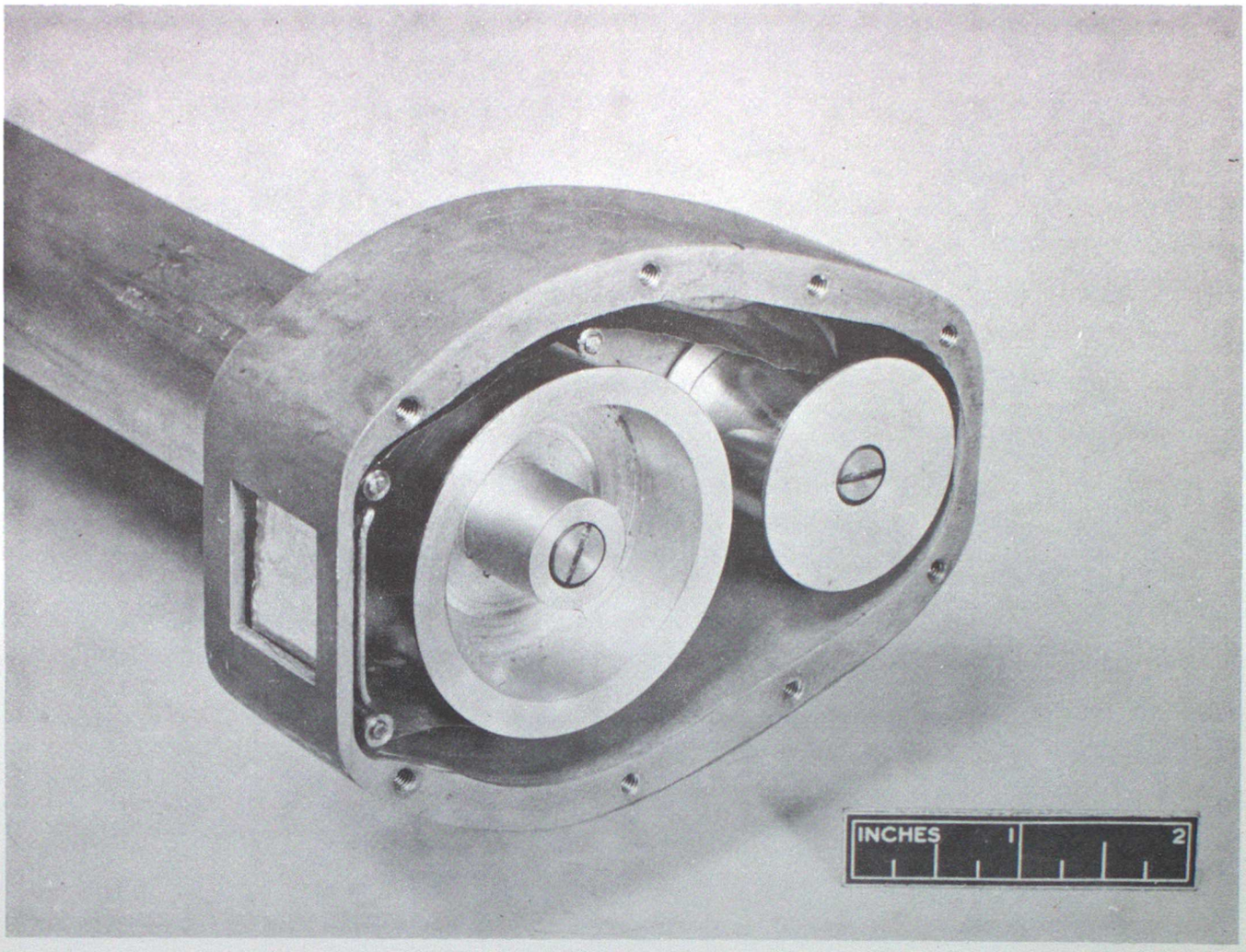


FIG.14 HEAD OF IMPACTOR FOR MEASURING RAINDROP SIZE

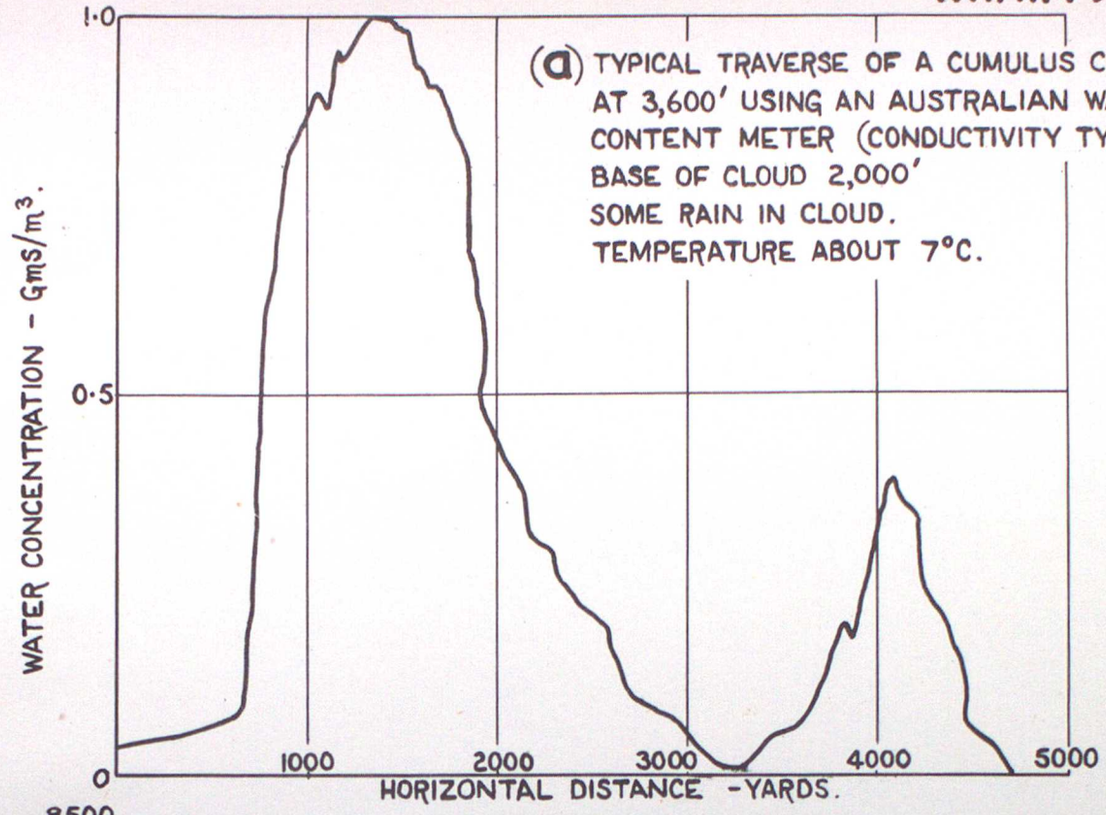
(end cover removed)

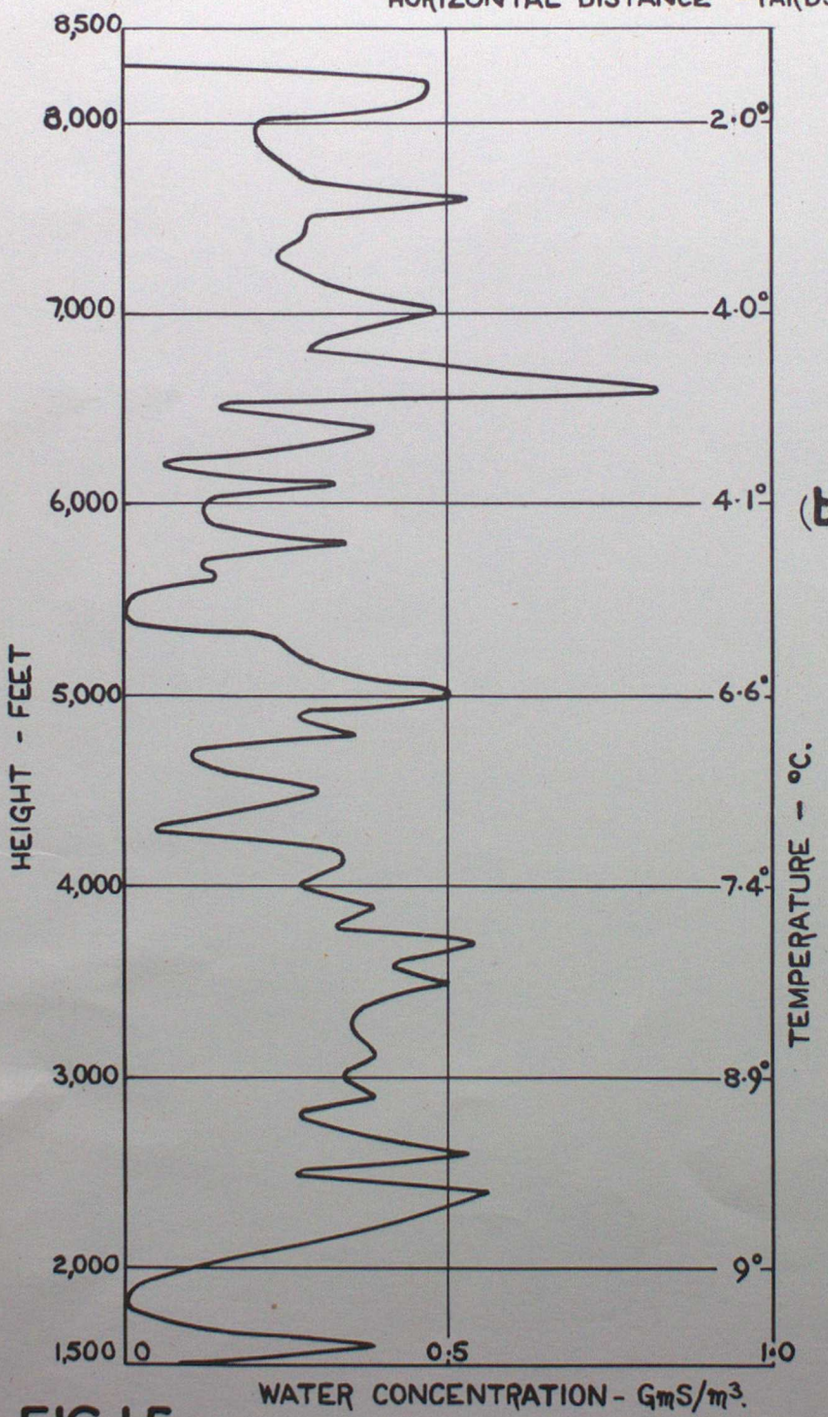
This instrument is exposed on the end of a pole through the aircraft skin and the take-up drum rotated electrically.

Raindrops produce indentations in the foil which can be counted and sized, thus obtaining a continuous record of the raindrop spectrum.

(a) TYPICAL TRAVERSE OF A CUMULUS CLOUD AT 3,600′ USING AN AUSTRALIAN WATER CONTENT METER (CONDUCTIVITY TYPE.)
BASE OF CLOUD 2,000′
SOME RAIN IN CLOUD.
TEMPERATURE ABOUT 7°C.

(a) & (b)





(b) ASCENT THROUGH A LAYER CLOUD - HOT WIRE WATER CONTENT METER.
CLOUD BASE 8/8 AT 1500′
RAINING FROM BASE.
CLOUD TOP 8,500′ PATCHES.
TO 9,700′.
NOTHING ABOVE.

FIG. 15.
(a) & (b) CLOUD WATER CONTENT MEASUREMENT.

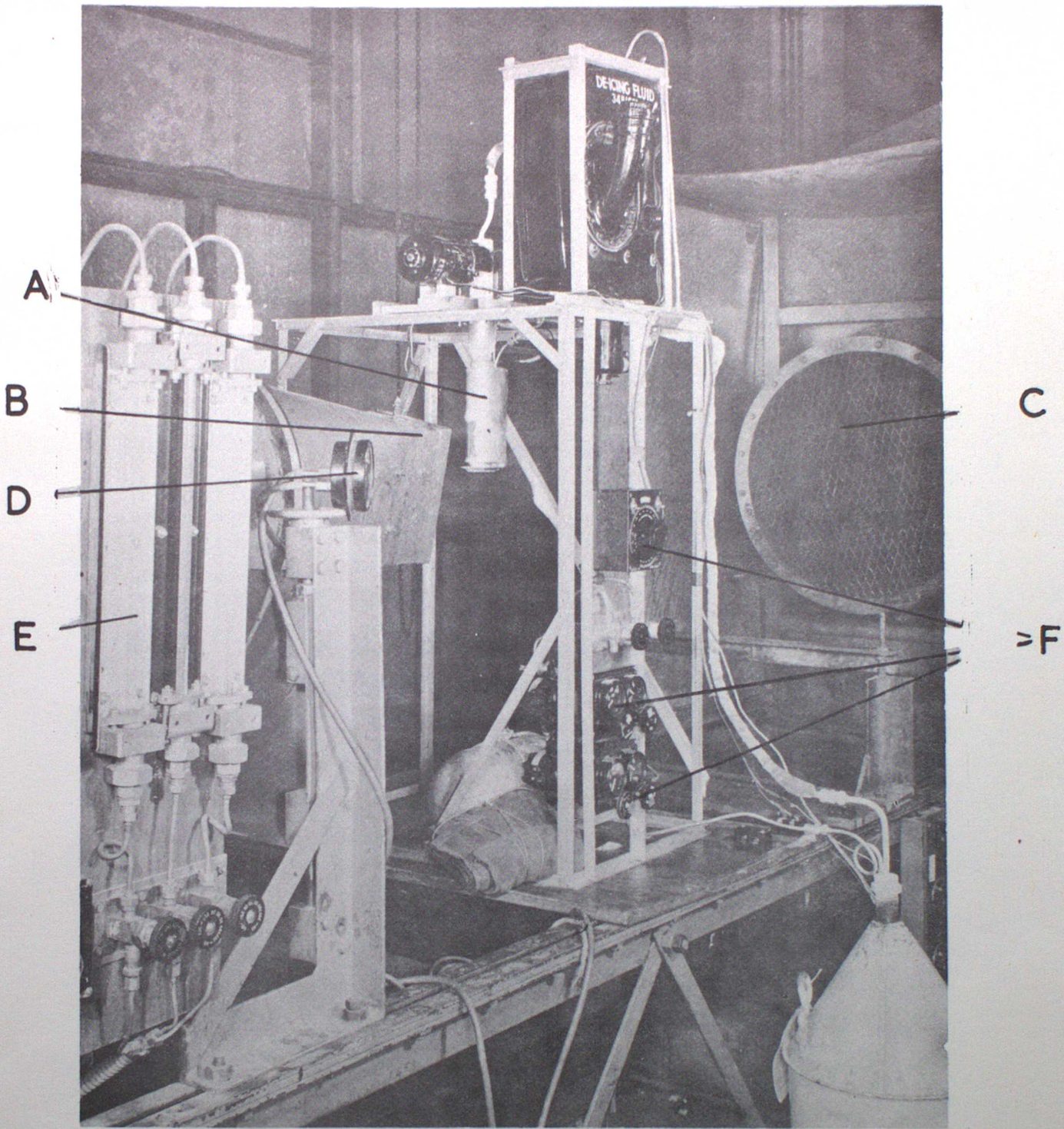
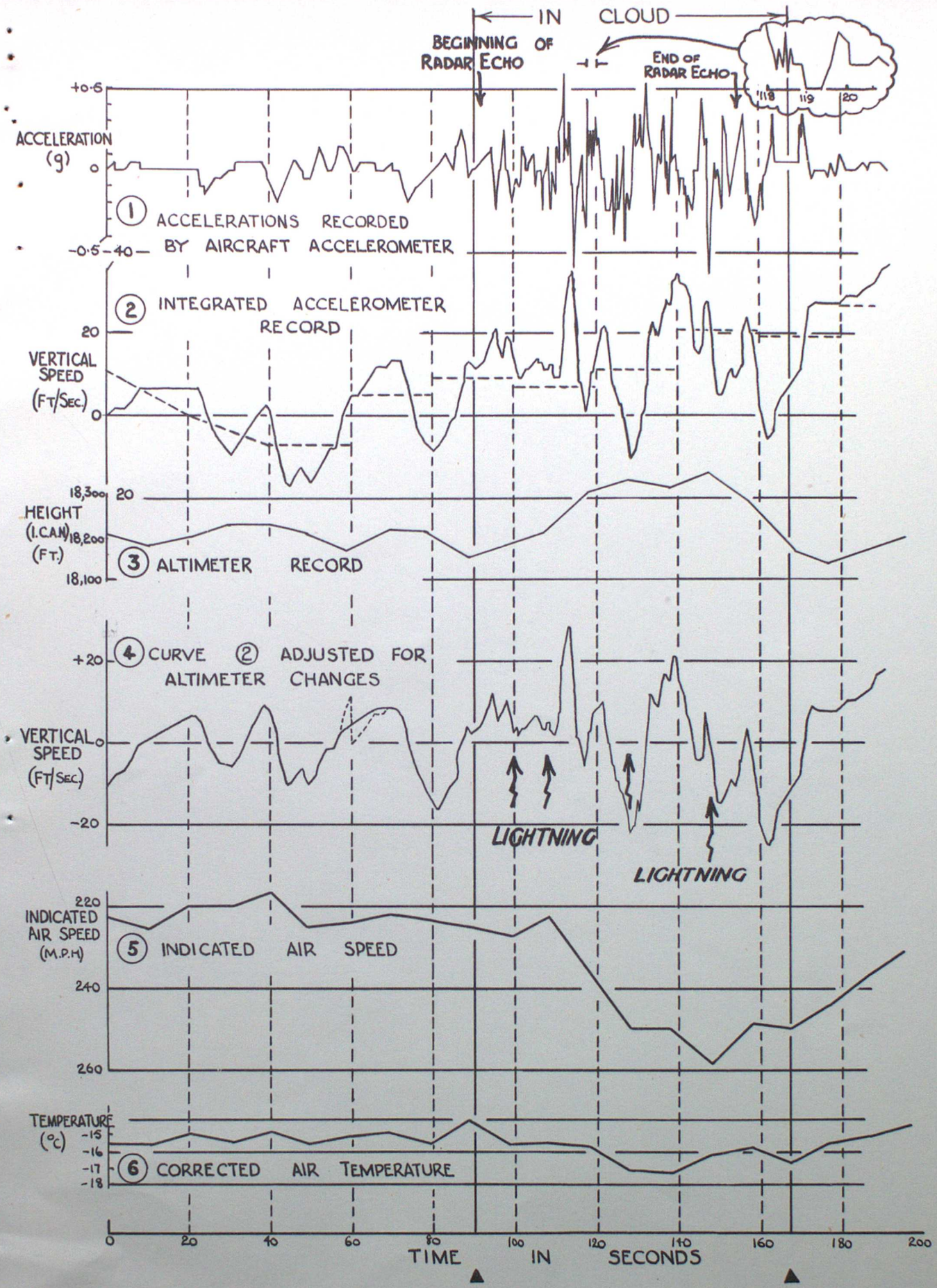


Fig. 16 WIND TUNNEL DEVELOPMENT OF REFRIGERATED ROTATING ICING DISC

The instrument to be tested is mounted on a frame near the open end of a wind tunnel. With this tunnel speeds up to 150 Kt., temperatures down to minus 20° Centigrade and water drop sizes of 10 microns to about 0.5 mm. can be obtained. After observation and calibration in the tunnel, the instrument is mounted on the aircraft for further development and use.

A Icing Meter under test
B Tunnel outlet
C Tunnel-fan intake
D Meter for measuring air-speed in tunnel
E Meter for measuring water supplied to tunnel
F Controls of Icing Meter



CUMULONIMBUS INVESTIGATION-13TH JUNE 1952-RUN 5-18,200'

FIG. 17

The graphs show the variations in height, airspeed and acceleration (bumpiness) as an aircraft traversed a large cumulonimbus cloud. Positions of radar echoes and lightning are also shown. By integrating the acceleration curve, the distribution of vertical up- and down-draughts (curve 4) was obtained.

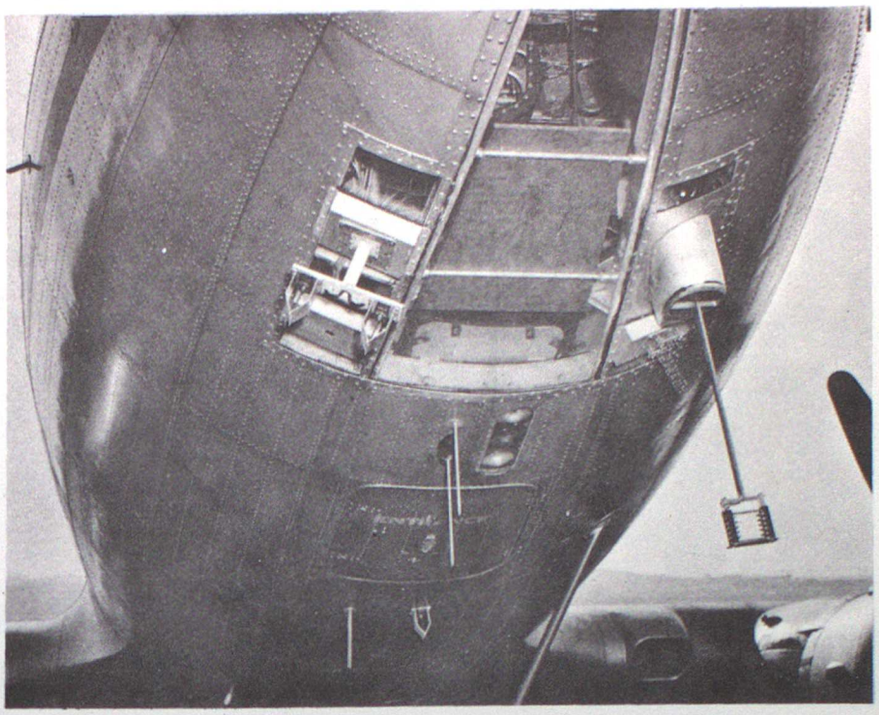


FIG. 18

On the right is the Ultra Rapid Thermometer which has a lag of a few micro-seconds only. It consists of very thin platinum wires (50 s.w.g.) mounted on a frame which is retracted into the fairing above for take off and landing and also in rain or icing conditions; changes in resistance are recorded by galvanometer or cathode ray tube.

On the left is a pair of experimental Flat Plate Resistance Thermometers.

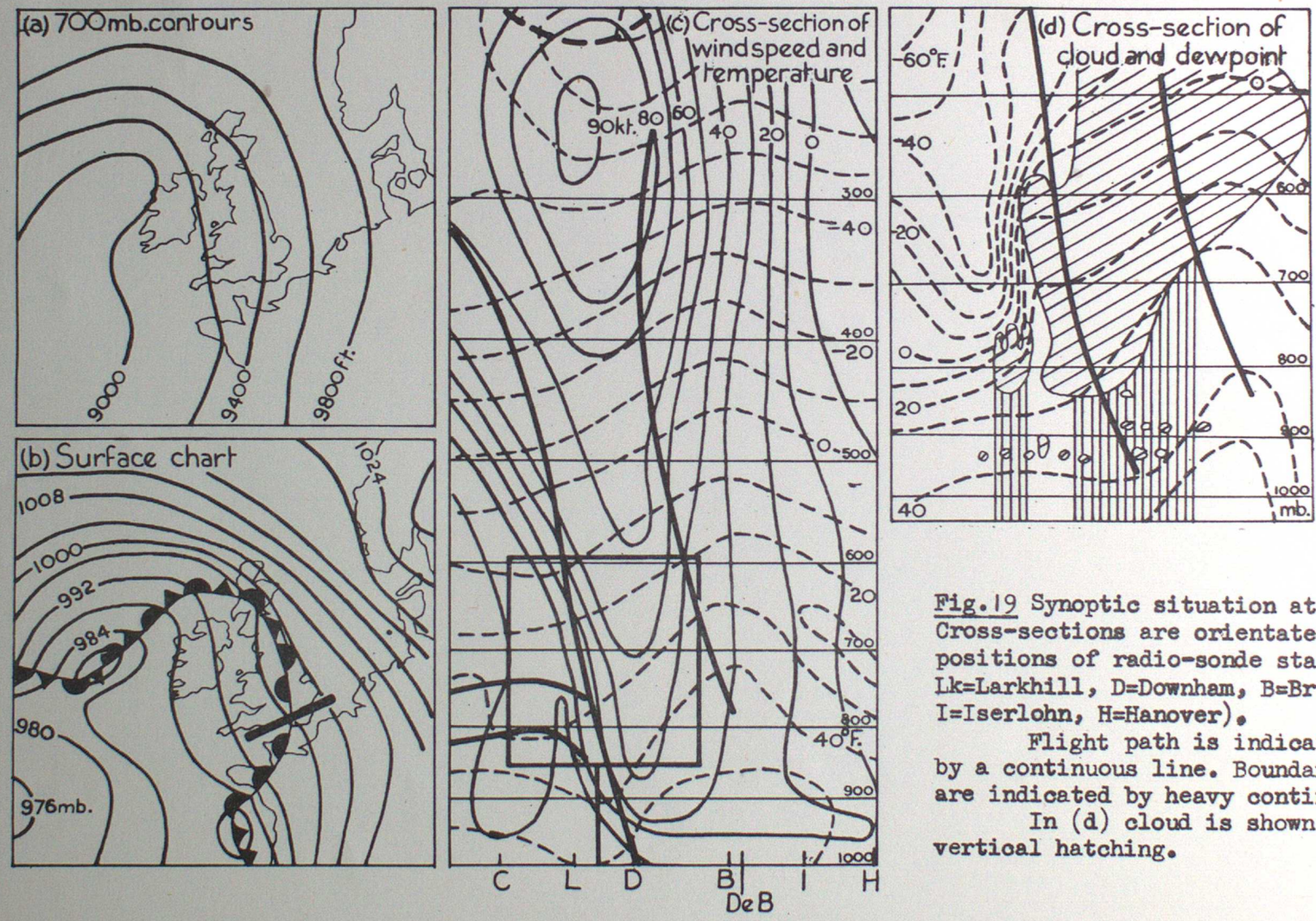


Fig.19 Synoptic situation at 1500 G.M.T. 5.11.51. Cross-sections are orientated east-west with approximate positions of radio-sonde stations indicated (C=Camborne, Lk=Larkhill, D=Downham, B=Brussels, DeB=De Bilt, I=Iserlohn, H=Hanover).

Flight path is indicated on diagrams (b) and (c) by a continuous line. Boundaries of the frontal zone are indicated by heavy continuous lines.

In (d) cloud is shown by diagonal, and rain by vertical hatching.

FIG.19 CROSS-SECTION THROUGH A FRONTAL SURFACE

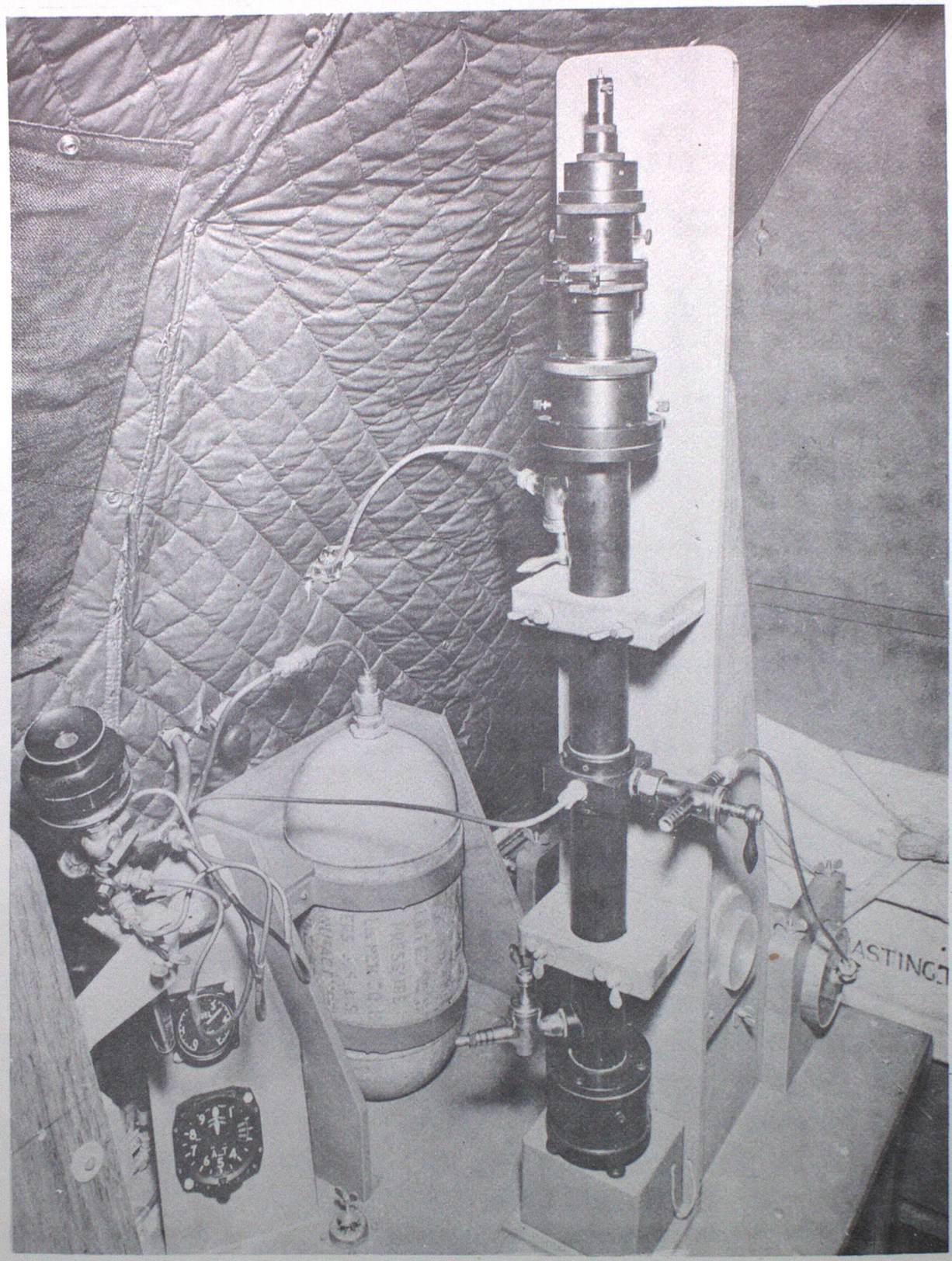


FIG.20 TWO CONDENSATION COUNTERS

On the left is an Aitken Counter which proved very difficult to operate in an aircraft.

On the right is the Pollak Counter modified for use in the air and used successfully on many flights. Air expanded in the main body of the instrument obscures light passing from the top to a photocell at the bottom. The density of the cloud is a measure of the number of nuclei present.

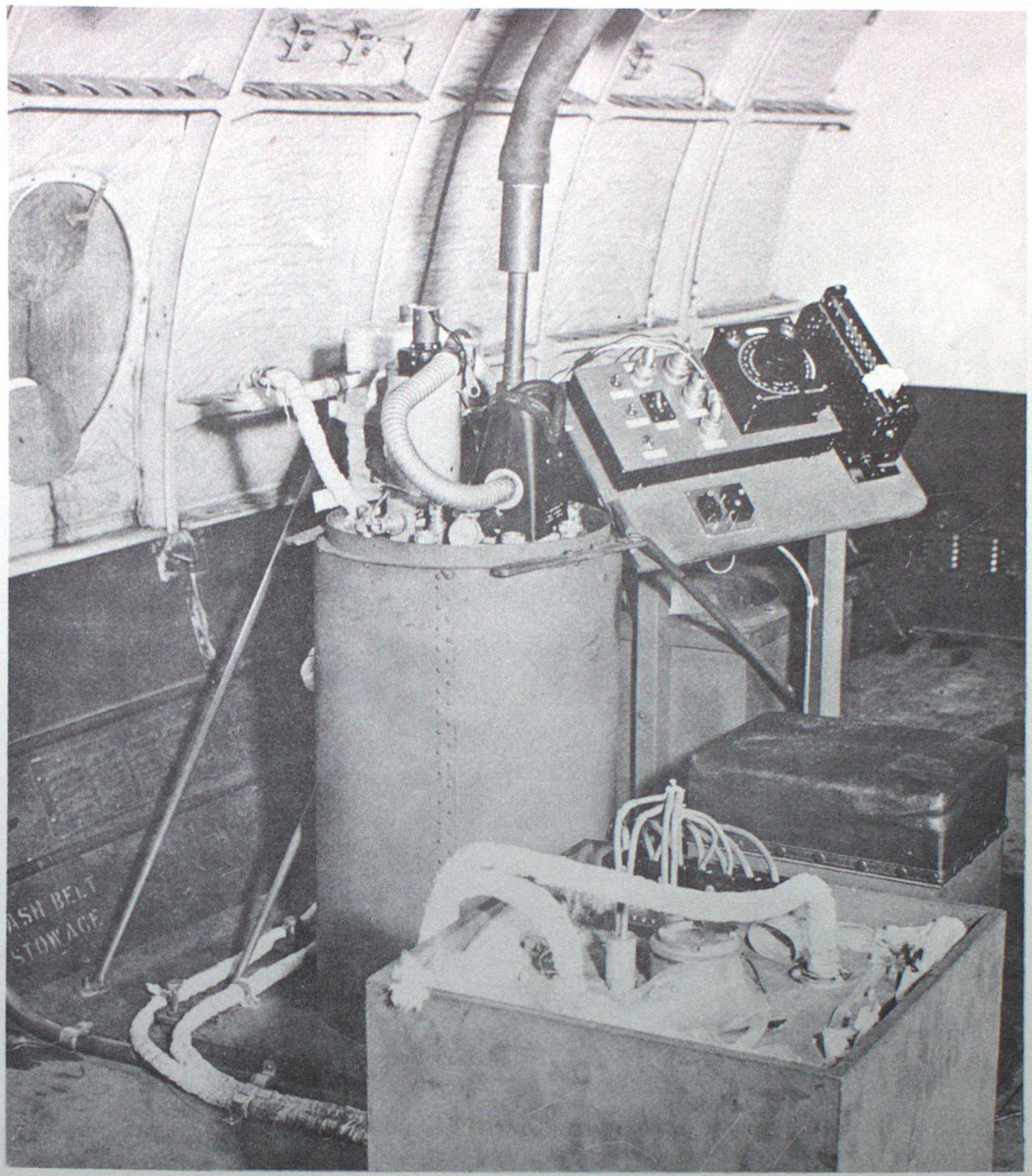


FIG.21 FREEZING NUCLEUS COUNTER

Air is inducted into the cylindrical chamber which is cooled by passing methylated spirits through pipes around it and a spiral immersed in solid carbon dioxide.

A small boiler provides steam inside the chamber which is also brightly illuminated by a beam of light from a high power lamp.

The observer, looking in the chamber, observes and estimates the number of ice crystals he can see at various temperatures. Ice crystals sparkle and glisten, whereas water droplets appear dull and opaque.

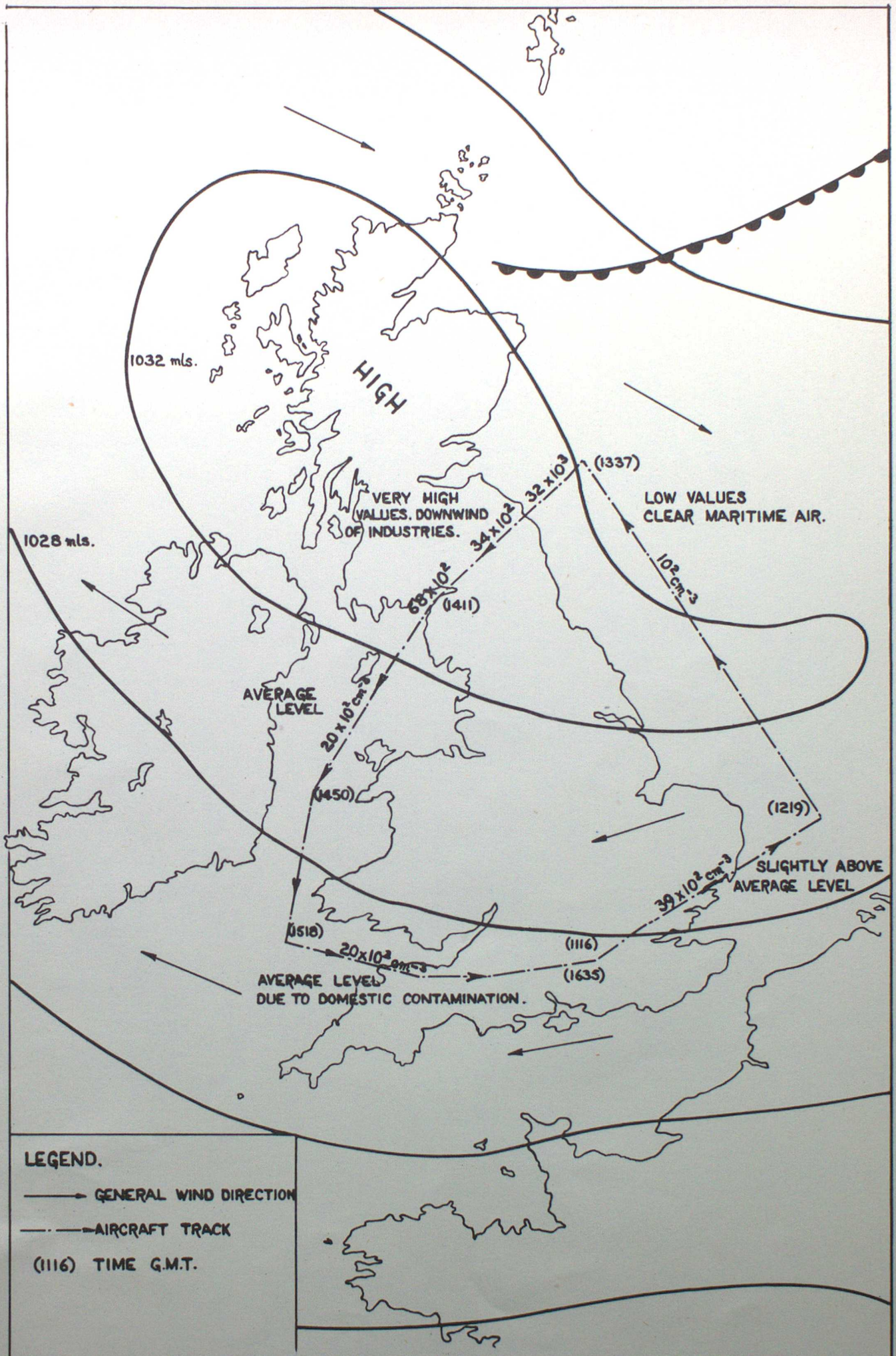


FIG.22. CONDENSATION NUCLEUS CONCENTRATION

OBSERVED ON A FLIGHT ON 30·3·55.

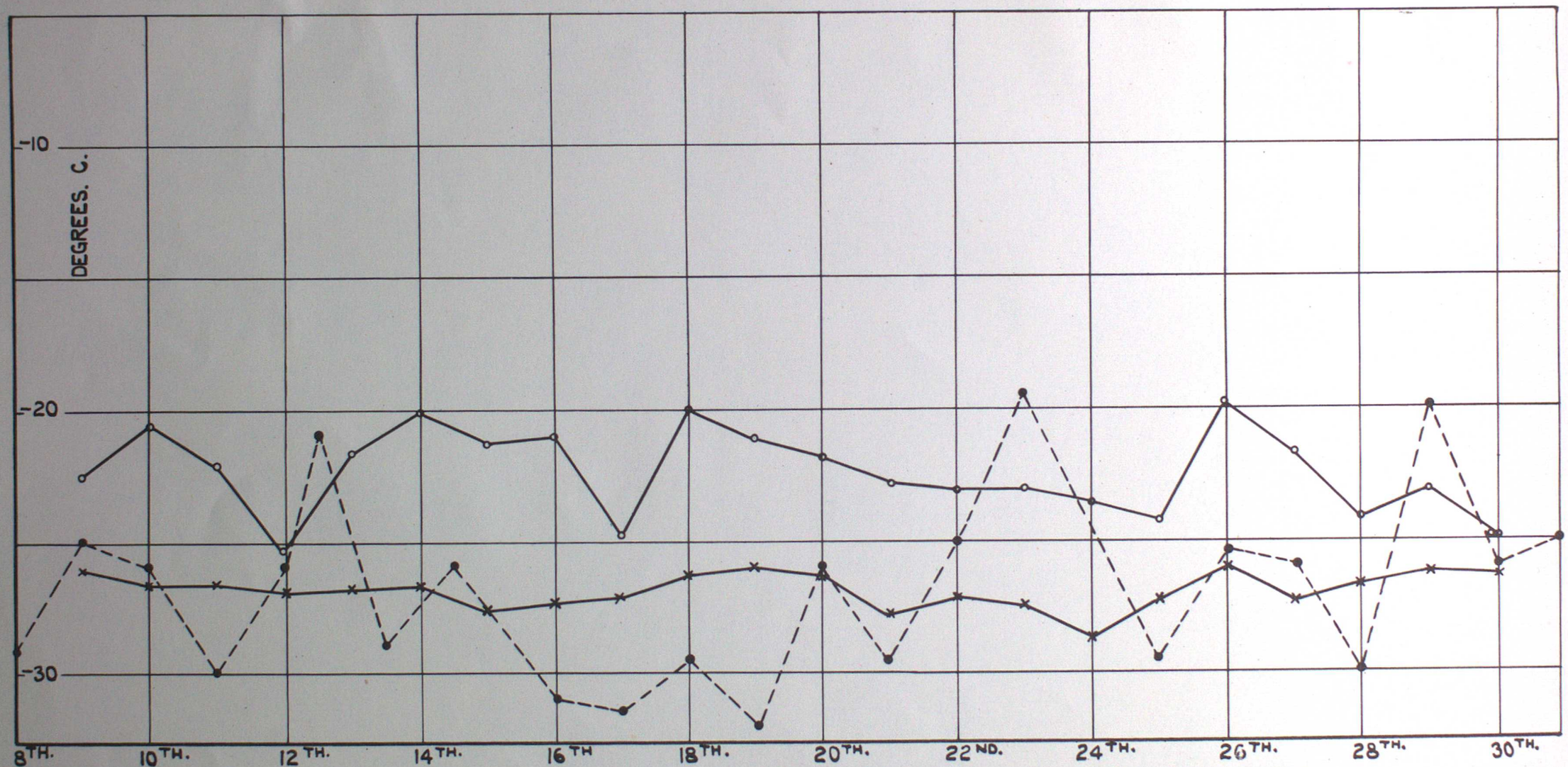


FIG. 23. A SEQUENCE OF FREEZING NUCLEI COUNTS.

(TEMPERATURES AT WHICH 1/LITRE AND 10^4/LITRE OBSERVED.)

(ONE MEASUREMENT EVERY DAY AT 10,000 FEET OVER SOUTHERN ENGLAND)
SIMILAR MEASUREMENT IN AUSTRALIA JAN. 1955. SHOWN DOTTED, 1/LITRE ONLY.

o—o 1/LITRE.
x—x 10^4/LITRE.

M.R.P. 995

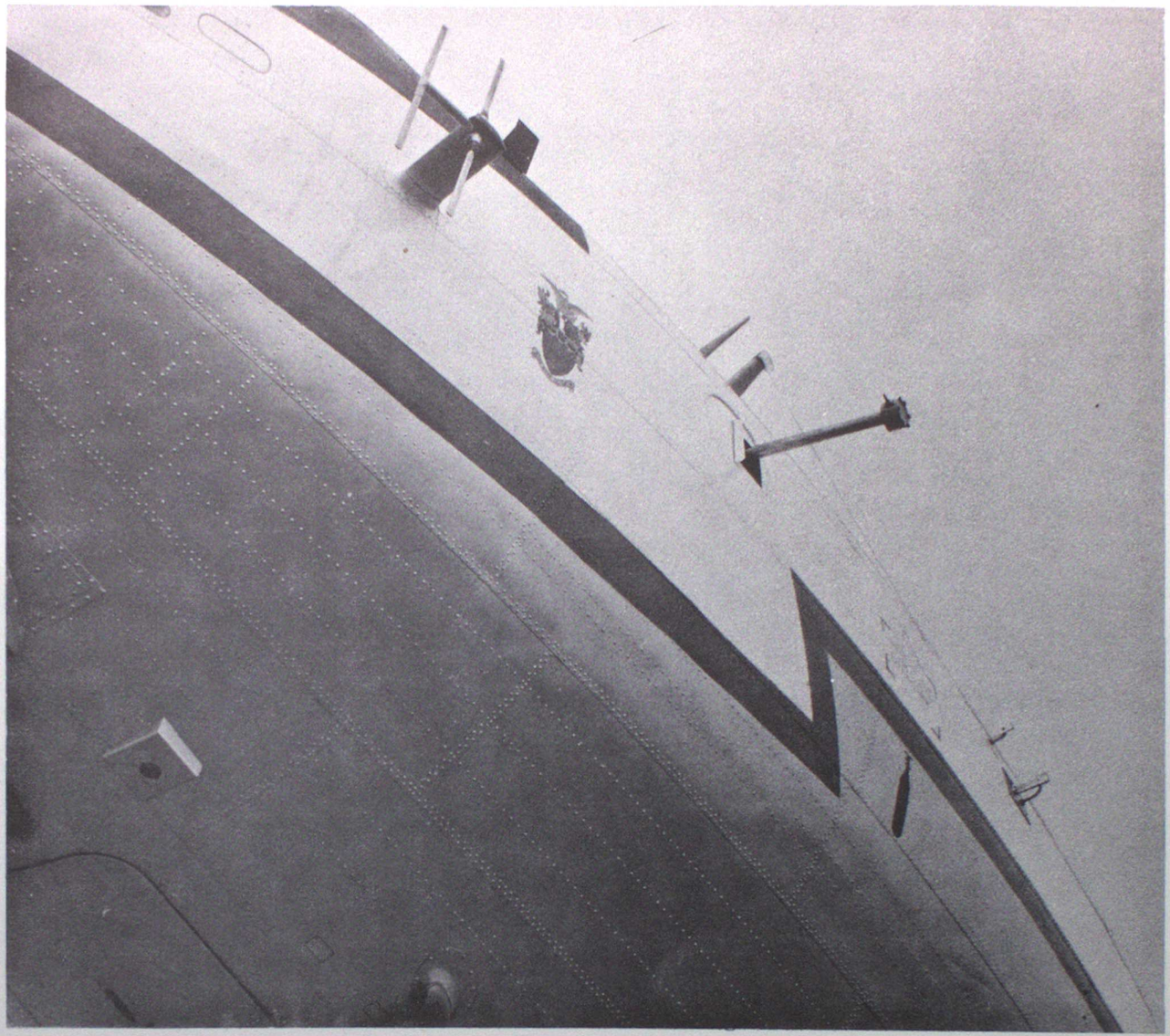


FIG. 24

Impactor for diffusion studies projecting from the side of the aircraft when in use. Afterwards it is retracted through the hole in the skin.

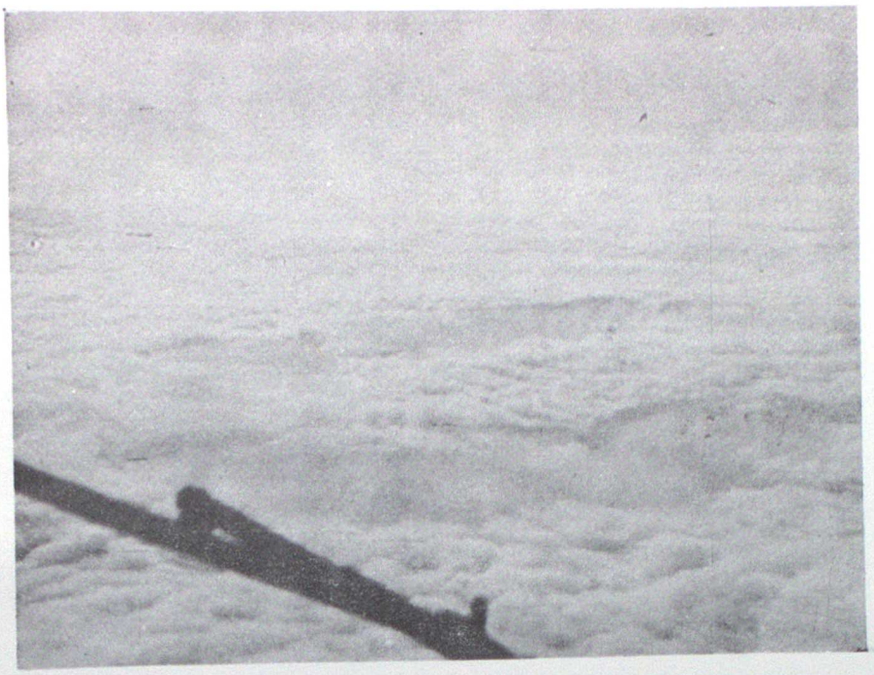
All the other impactors described in this article can be exposed in a similar manner.

SEEDING EXPERIMENT 9.1.56 at 1100 HRS. M.R.P. 995

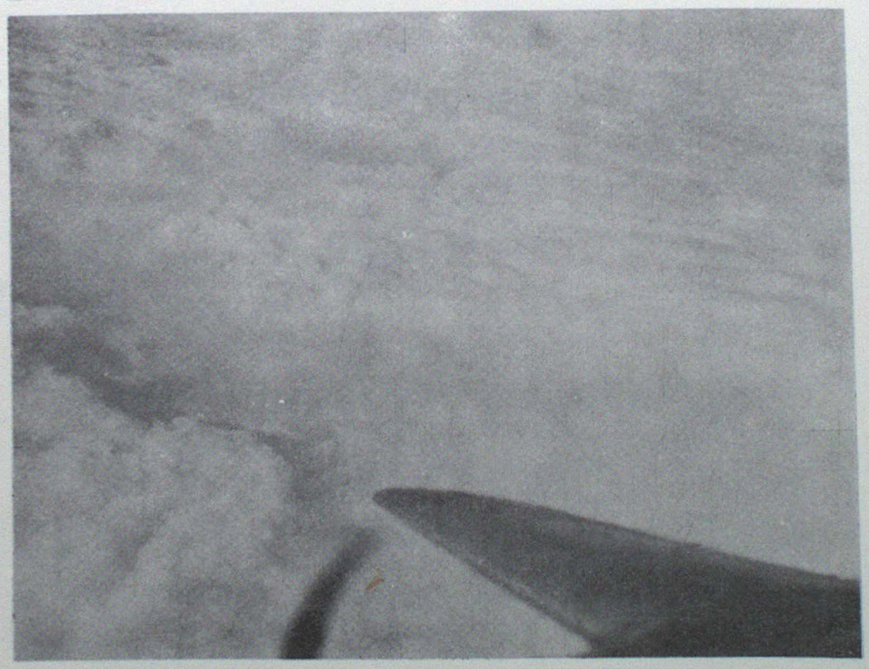
STRATOCUMULUS LAYER, BASE 2,200 FT. AT +27.5°F., TOP 4,500 FT. AT +21.0°F

AIRCRAFT FLEW AN 'S' CURVE 100 FT. ABOVE TOPS. DRY ICE SEEDING 70 LBS.

IN 3½ MINUTES (6LBS. PER MILE APPROX.)



14 MINS. AFTER SEEDING.
FIBROUS LANES APPEAR
IN CLOUD TOPS.



22 MINS. AFTER SEEDING.
CLOSE UP OF SEEDED AREA
SHOWING 'S' SHAPE.

28 MINS. AFTER SEEDING.
SUN PILLAR REFLECTION;
DISTORTION OF 'S' SHAPE
WITH SHARP EDGE TO
SEEDED AREA.

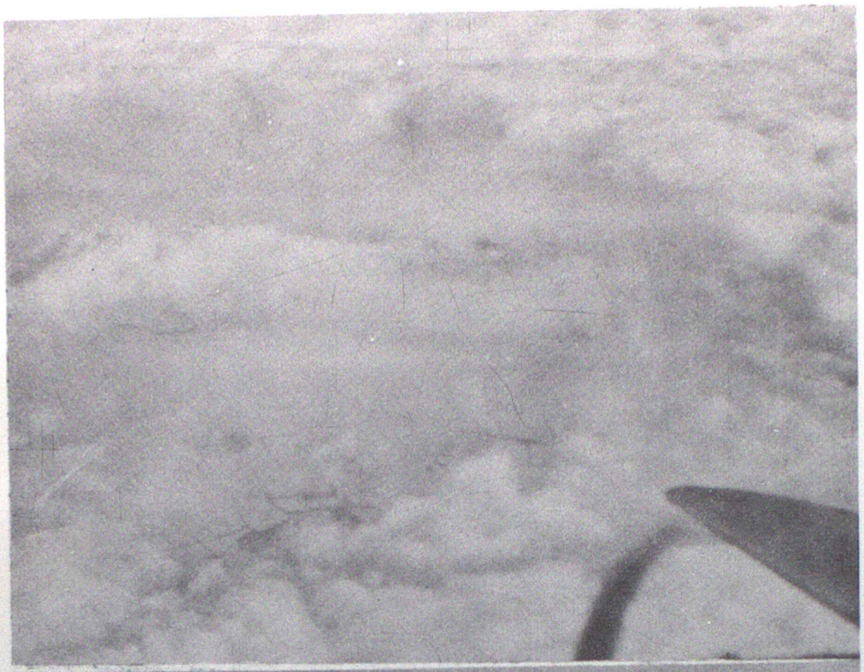
FIG. 25

SEEDING EXPERIMENT 9.1.56 at 1100 HRS M.R.P.995

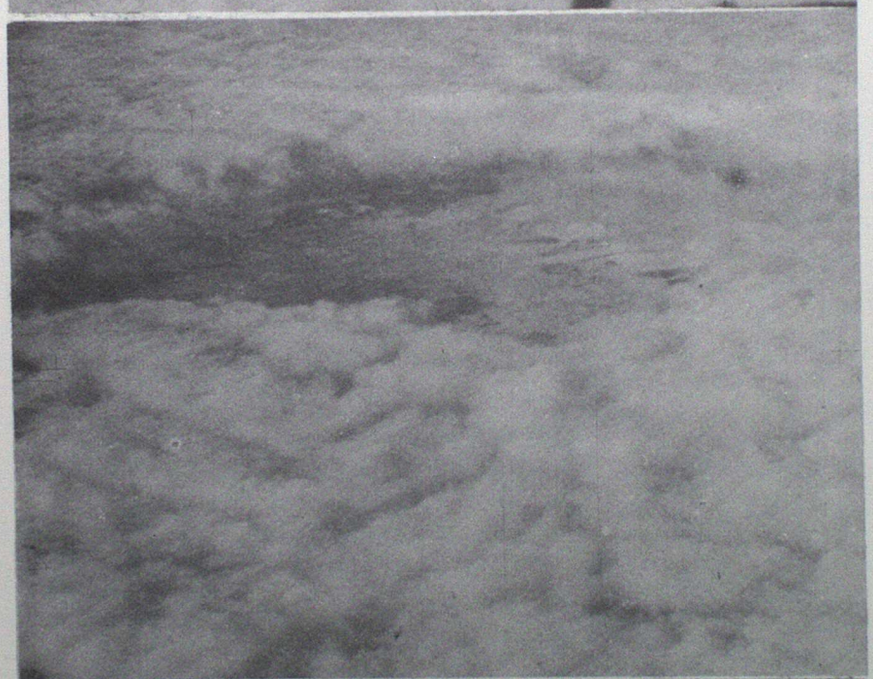
STRATOCUMULUS LAYER, BASE 2,200 FT. AT +27.5°F., TOP 4,500 FT.AT +21.0°F.

AIRCRAFT FIEW AN 'S' CURVE 100 FT. ABOVE TOPS. DRY ICE SEEDING 70 LBS.

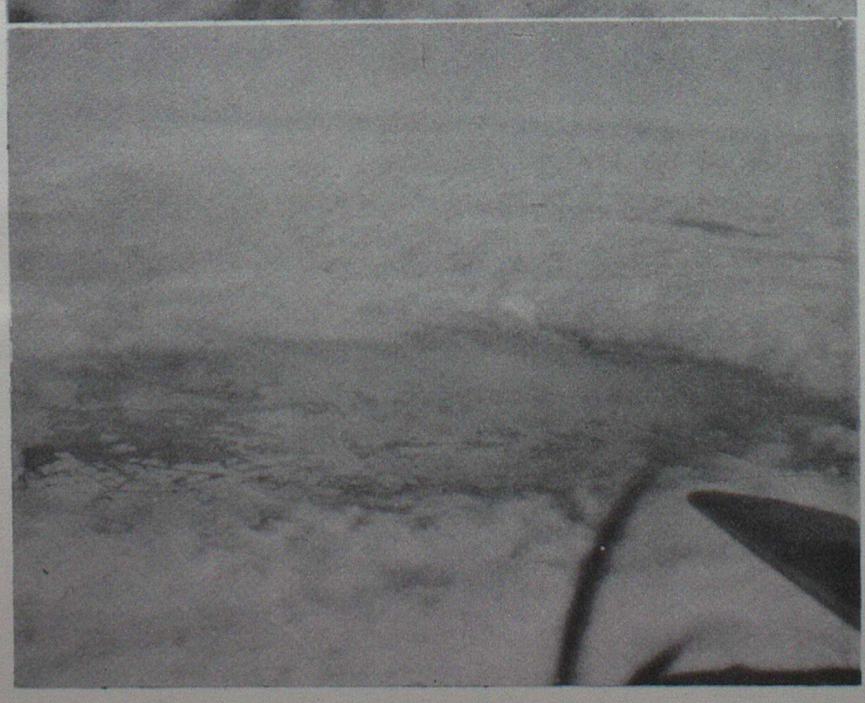
IN 3½ MINUTES (6 LBS PER MILE APPROX.)



37 MINS. AFTER SEEDING,
GROUND FIRST SEEN.



48½ MINS. AFTER SEEDING,
GROUND CLEARLY VISIBLE
HOLE PROBABLY 5 MI.ACROSS.



50½ MINS.AFTER SEEDING.
END OF EXPERIMENT. HOLE
NOW ABOUT 30 MI. DOWN-
WIND OF ORIGINAL SEEDED
LOCATION.

FIG.25 (CONT.)

M.R.P. 995

RADAR P.P.I. PHOTOGRAPHS DURING SEEDING EXPERIMENT

OF 23.1.52

(a)... First semicircle forming.
23 minutes after seeding.

(b)... First semicircle well marked.
25m. 50 sec. after seeding.

(c)... Signs of second semicircle.
31m. 20 sec. after seeding.

(d)... Second semicircle also well marked.
34m. 20 sec. after seeding.

(e)... Semicircles drifting apart.
35m. 03 sec. after seeding.

FIG.26. The aircraft dropped dry ice in a semicircle through two layers of supercooled stratocumulus cloud.

Seeding commenced at 1522 hours. Area of permanent echo is enclosed. P.P.I. range markers are at five mile intervals. Cloud reflections are in northeast quadrant.

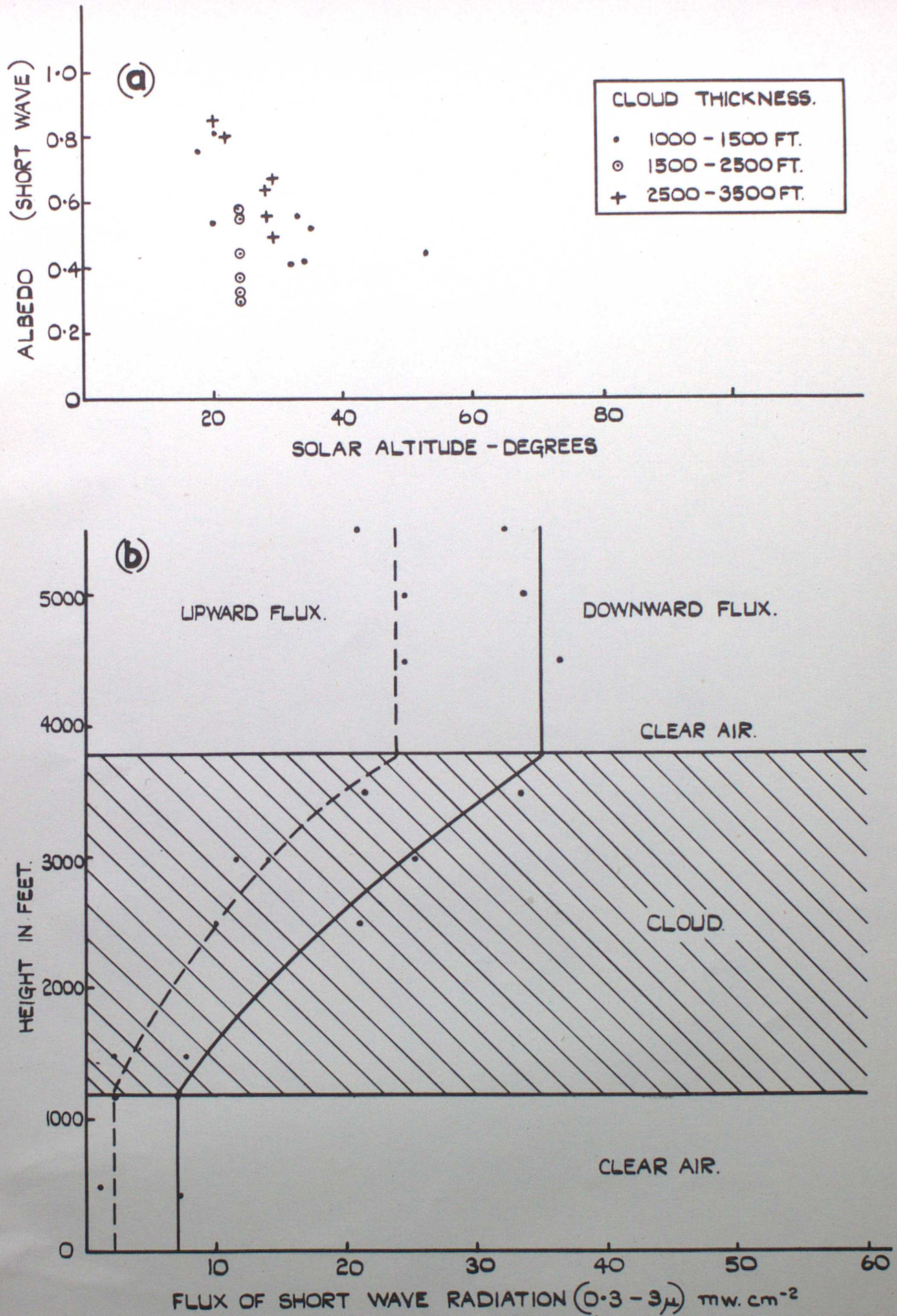
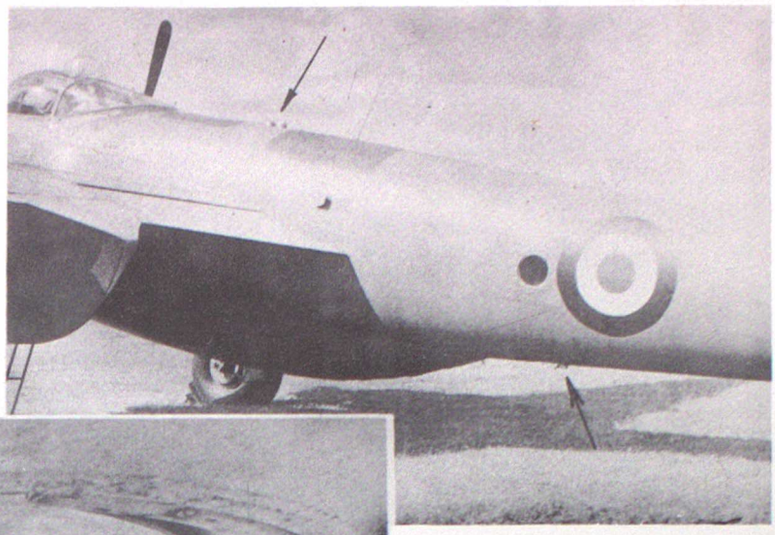


FIG.27

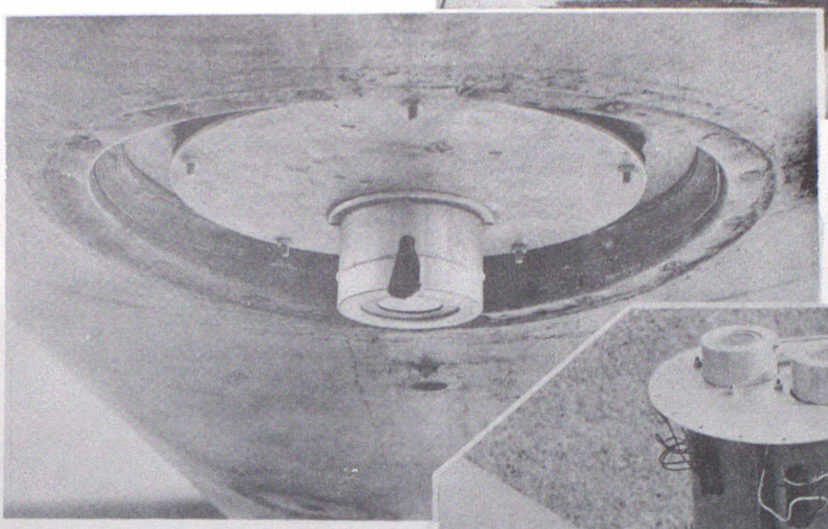
ALBEDO MEASUREMENTS FROM AIRCRAFT.

(a) FLIGHT RESULTS ABOVE SUNLIT STRATOCUMULUS.

(b) TYPICAL VARIATION THROUGH A CLOUD LAYER.

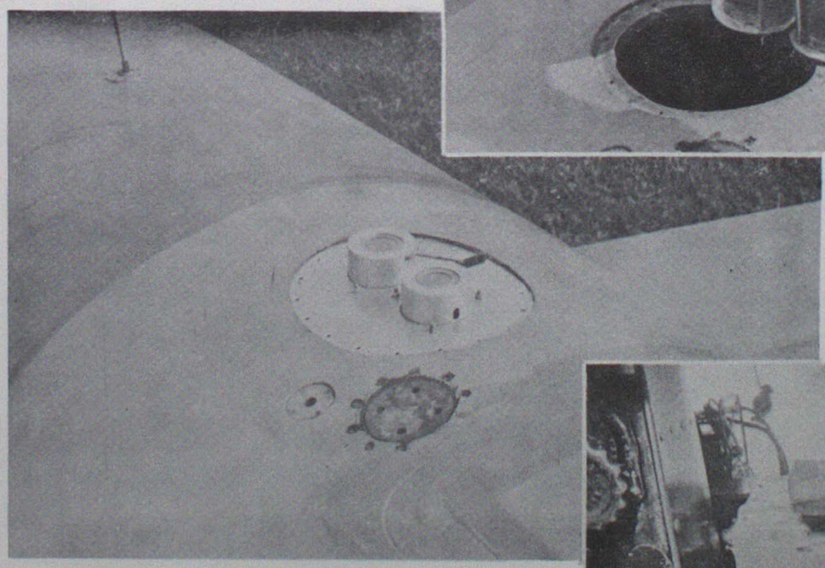


MOSQUITO AIRCRAFT (POSITIONS OF RADIOMETERS INDICATED BY ARROWS

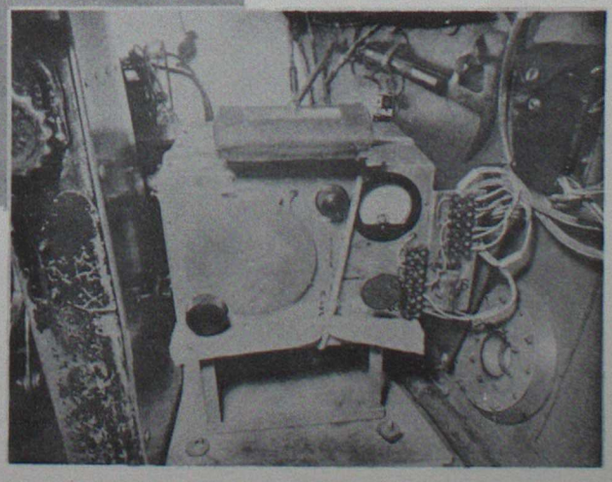


DOWNWARD-FACING RADIOMETER

UPWARD-FACING RADIOMETERS



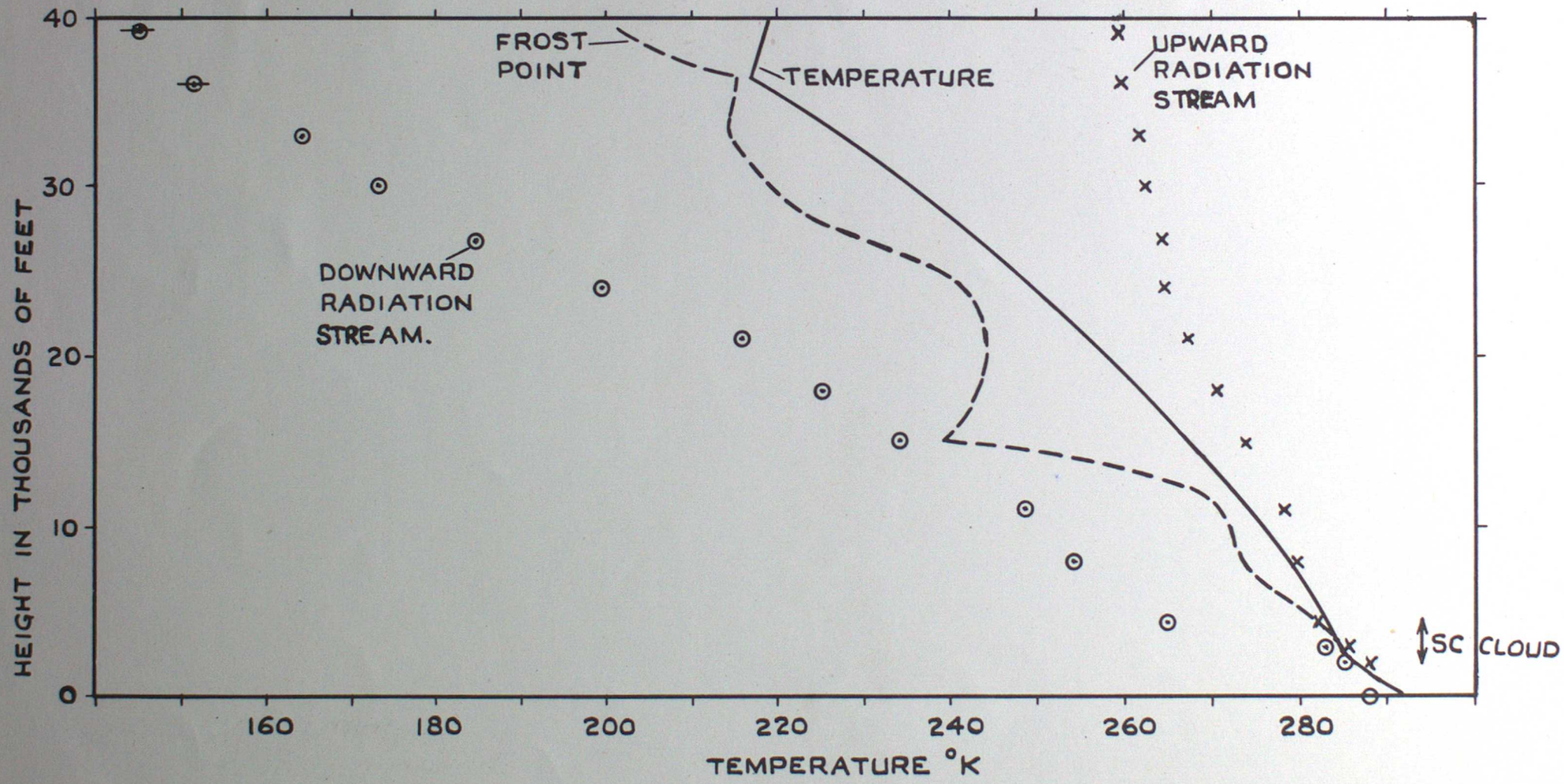
UPWARD-FACING RADIOMETERS



MEASURING BRIDGE IN CABIN OF AIRCRAFT

FIG.28

THE USE OF RADIOMETERS FOR MEASUREMENT OF LONG WAVE RADIATION USING A MOSQUITO AIRCRAFT OF THE METEOROLOGICAL RESEARCH FLIGHT



TYPICAL MEASUREMENT OF UPWARD & DOWNWARD

FIG. 29. LONG WAVE (4-50 μ) RADIATION AT NIGHT.
(Expressed as equivalent black-body temperature)

M.R.P.995